difficult to ignore. An illustrative example of such a curve is shown in Exhibit 11.

Exhibit 11 is an illustrative sketch of the normalized probability of a strong year class of a key species plotted against the distance downstream of the near-bottom 2 ‰ isohaline. The lower curves represent the level of uncertainty associated with the estimates. The figure indicates that within the zone extending from the origin to X_1, the slope of the curve is nearly flat, indicating that the probability of a strong year class changes little within this region of the system. This zone might correspond to the region of the delta where displacement of the 2 ‰ isohaline farther seaward yields relatively little ecological benefit because of the controlling influence of entrainment losses. Seaward of this zone from X_1 to X_2, the probability of a strong year class increases relatively rapidly with increased displacement of the 2 ‰ downstream. Seaward of X_2, the rate of increase again flatters out and displacement of the 2 ‰ isohaline beyond some limit may actually decrease the probability of a strong year class.

The proposal is to construct a series of such curves for appropriate life history stages of key species of the San Francisco Bay-Delta estuary and to aggregate them by season. The next step is to use the family of curves for each season to select a position of the near-bottom 2 ‰ isohaline that would provide an appropriate level of ecological protection for the sum of these species, and presumably for protection of the estuary, that is based upon the best scientific evidence available. The position of the near-bottom 2 ‰ isohaline selected for each season would be the salinity

standard for that season. Riverflow and diversion would be modified to ensure that the 2 ‰ isohaline did not migrate farther upstream than the position associated with the salinity standard.

EXHIBIT 10

THE MATRIX
AN EXAMPLE OF A MATRIX TO USE IN IDENTIFYING THE APPROPRIATE POSITION FOR LOCATING THE 2 ‰ NEAR-BOTTOM EFFECTS ON VARIOUS PROCESSES AND PROPERTIES BY PLACING ISOHALINE AT DIFFERENT LOCATIONS WITHIN THE ESTUARY
(SEASON ____)

PROCESSES AND PROPERTIES	SALINITY MEASURED 2PPT + 1 M FROM BOTTOM		
	LOCATION 1 (Farthest Upstream)	LOCATION 2	LOCATION 3 (Farthest Downstream)
FW FLOW			
FW & EZ HABITAT			
TURBIDITY MAXIMUM			
SUSPENDED SEDIMENTS			
Mass			
Lost to System			
Budget			
INPUTS AND FATES OF			
PARTICLE-BOUND TOXICS			
VOL. AGR. RETURN WATER			
PHYTOPLANKTON			
Prim. Productivity			
Biomass			
Distribution			
Abundance			
NEOMYSIS			
MARINE & EST. FISHES			
UPSTREAM LIMITS			
Vol. of habitat			
Abundance			
Suscept. to Delta Div.			
To entrainment			
Survival of yr. class			
Food supply			
Migration			
TIDAL MARSH			
MANAGED MARSH			
INVASION BY MARINE SPP.			
ENDANGERED SPP.			

EXHIBIT 11

A Graphical Tool for Selecting
a Salinity Standard
for San Francisco Bay and Delta

Distance downstream of near-bottom 2‰ isohaline
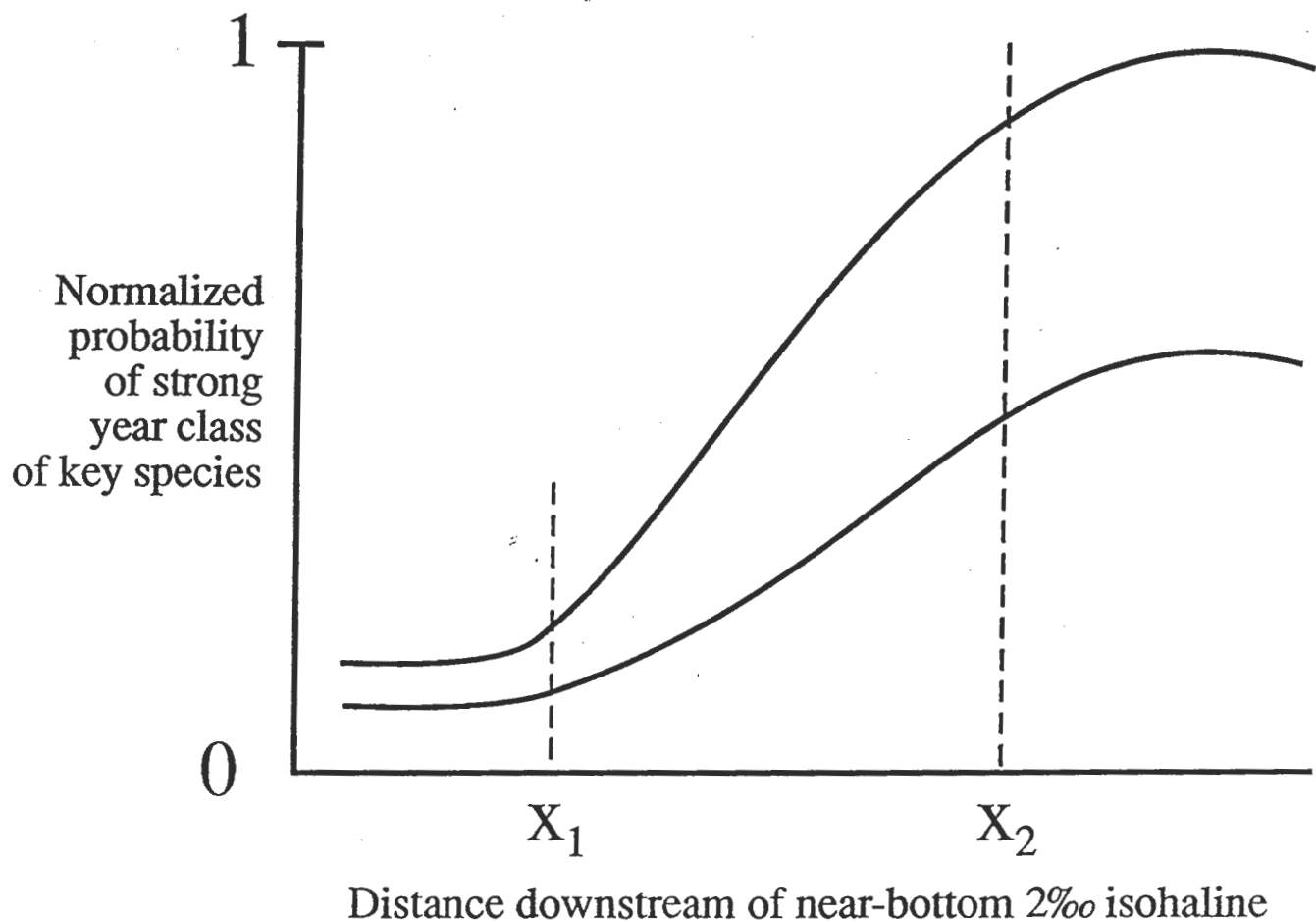
CONCLUSIONS AND RECOMMENDATIONS

Members of the workshop recommend in the strongest terms possible that the strategy of assessing the effects associated with different flow scenarios and salinity responses outlined in this report be refined, enriched and extended using the best scientific and technical information possible. We recommend further that the results of this analysis should be used to set temporary seasonal salinity standards for managing freshwater inflows to the San Francisco Bay estuary.

The San Francisco Estuary Project should form a working group that draws together the best scientific and technical minds to refine the matrix, to complete the scientific and technical analysis required to produce the curves needed to set the seasonal salinity standards and to establish the levels of uncertainty associated with the predicted effects. The Working Group should involve the best scientists and engineers from agencies, academic institutions, environmental groups and consulting companies who have the required expertise. Heads of these agencies should ensure that the appropriate individuals are available and committed to this effort.

The analysis should be done outside of any federal or state agency and should be decoupled from on-going policy analyses. The objective of the analysis should be to provide, with existing information, the most rigorous scientific basis possible, for defining for each season the

24

position of the near-bottom 2 ‰ isohaline to protect important ecosystem functions, values and uses. The results of this analysis can be used to evaluate the consequences of different water-use policy alternatives on the estuary and its living resources, but it should not be captive to the policy process. The analysis should be completed and become the input for a second workshop to be held no later than 31 December 1991.

The working group should attempt to anticipate and address questions that managers, regulators and policy makers will ask. These include such questions as:

(1) How much water discharge is required and for how long to achieve the desired results? What are the advantages and disadvantages of pulsing versus a continuous, uniform discharge?

(2) If diversion of water from the Delta were eliminated during summer months, could the upstream limit of the 2 ‰ bottom isohaline be moved farther upstream? If so, how far? If not, why not?

The results of the analysis should provide a template for an expanded research and monitoring program targeted at reducing critical areas of uncertainty in the effects associated with fixing the position of the 2 ‰ isohaline at different locations.

Some important research topics that should be pursued are summarized in Exhibit 12.

EXHIBIT 12

SOME IMPORTANT RESEARCH QUESTIONS

- What are the relationships between inflow, Delta outflow, tides and the salt field? How well do the existing relationships between biological entities and flows translate into relationships with the position of the 2 ‰ isohaline?

- How are biologically important materials transported from the rivers either to the estuary or to the export pumps, and how does this transport change with position of the 2 ‰ isohaline?

- What role does the exchange of particles and organisms between shoals and channels play in mediating the observed relationships between EZ position, biological abundance and year class strength?

- To what extent are the observed relationships between biological entities (abundance or year class strength) and flow or EZ position a function of food limitation as opposed to direct physical control or other alternative mechanisms?

- What are the important sources, sinks, and fates of organic matter and sediment in the estuary, and how do these vary with position of the 2 ‰ isohaline?

APPENDICES

APPENDIX A

AGENDA

27 AUGUST 1991

0900	I. Welcome & Introductions	T. Vendlinski G. Thomas W. Kimmerer J.R. Schubel
0915	II. Background on Workshop: How We Got To Where We Are	T. Vendlinski
0930	III. Some Environmental Management Goals to Guide the Workshop	G. Thomas T. Vendlinski
1000	IV. An Overview of the Workshop: Objectives; Format; Ground Rules; Measures of Success	J.R. Schubel
1030	Break	
1100	V. Review and Clarification of the Eight Issues	W. Kimmerer et al.
1230	Lunch	
1330-1500	V. Review and Clarification of the Eight Issues, Continued	
1500	Break	
1530	VI. Wrap-up and Recap of Discussion of the Big "8"	W. Kimmerer J.R. Schubel
1630	VII. Brainstorming Session to Identify Other Potential Surrogates For Managing Freshwater Inflows To Protect the Ecosystem and Important Societal Values and Uses of the San Francisco Bay-Delta Estuary	J.R. Schubel, Facilitator

1700	VIII.	Preliminary Ranking of Surrogates For Managing Freshwater Inflows	J.R. Schubel,
1730	IX.	Recap	
1800		Adjourn	

28 AUGUST 1991

0900	I.	A Brief Recap and Overview of the Day	J.R. Schubel, Facilitator
0930	II.	Scientific and Technical Assessment of the EZ and Other Top Candidates As Facilitator Surrogates for Managing Freshwater Inflows	J.R. Schubel,
	A.	Plenary	
	B.	Working Groups, as appropriate	
1030		Break	
1100	II.	Continuation of Scientific and Technical Assessment of the EZ and Other Top Candidates As Surrogates for Managing Freshwater Inflows	
1200		Lunch	
1300	II.	Continuation of Scientific and Technical Assessment of the EZ and Other Top Candidates As Surrogates for Managing Freshwater Inflows	
1430	III.	Ranking of the Surrogates	J.R. Schubel, Facilitator
1500		Break	
1530	IV.	Discussion of Ranking	J.R. Schubel, Facilitator
1630	V.	Brief Summary	J.R. Schubel

1700	VI.	Identification of Specific Research Questions and Hypotheses to Reduce the Facilitator Level of Uncertainty of the Value of Selected Surrogates and For Development of Others; Short-term, Intermediate-term and Long-term Research Strategies	W. Kimmerer, Facilitator

1800   Adjourn

29 AUGUST 1991

FROM SCIENCE TO POLICY

0900	I.	Overview & Summary of Days 1 & 2; The Goals Revisited	J.R. Schubel
0930	II.	(Continuation of Item VI on Previous Day) Identification of Specific Research Questions and Hypothese to Reduce the Level of of Uncertainty of the Value of Selected Surrogates and For Development of Others; Short-term, Intermediate-term and Long-term Research Strategies	W. Kimmerer

1030   Break

1100	III.	Discussion of the Range of Options for Selecting Goals for Improving Environmental Conditions in San Francisco Bay Estuary	T. Vendlinski G. Thomas

1200   Lunch

1300	III.	Discussion of the Range of Options for Selecting Goals for Improving Environmental Conditions in San Francisco Bay Estuary	T. Vendlinski G. Thomas

APPENDIX B

Bay Fisheries
Charles Armor
CADFG
4001 North Wilson Way
Stockton, CA 95205
(209) 466-4421

Phytoplankton/EZ
James Arthur
USBR
MP-780, Room W-2127
2800 Cottage Way
Sacramento, CA 95825
(916) 978-4923

Phytoplankton/ETZ
Douglas Ball
USBR
MP-780, Room W-2127
2800 Cottage Way,
Sacramento, CA 95825
(916) 978-4923

Technical/Policy
Randall Brown
DWR
3251 "S" Street
Sacramento, CA 95816
(916) 653-2635

Policy
Peter Chadwick
CADFG
4001 North Wilson Way
Stockton, CA 95205
(209) 466-4421

Primary Production
James Cloern
USGS
MS-496,
345 Middlefield Road
Menlo Park, CA 94025
(415) 354-3357

Striped Bass
James Cowen
Chesapeake Biological Lab
P.O. Box 38
Solomons, MD 20688
(301) 326-4281

Engineering/Modeling
Michael Ford
DWR
3251 "S" Street
Sacramento, CA 95816
(916) 653-0735

Water Policy
David Fullerton
NHI
2017 Berkeley Way
Apt. #7
Berkeley, CA 94704
(415) 540-5226

Fisheries/Biology
Charles Hanson
Consultant
500 Ignacio Valley Road
Suite 250
Walnut Creek, CA 94596
(415) 942-3133

Regulatory
Susan Hatfield
US EPA
75 Hawthorne Street
W-3-1
San Francisco, CA 94105
(415) 744-1997

Flows/Fisheries
Perry Herrgesell
CADFG
4001 North Wilson Way
Stockton, CA 95205
(209) 466-4421

Carbon/Phytoplankton
Alan Jassby
UCD
Div. of Environmental Studies
Davis, CA 95616
(916) 752-3938

EZ Physics
David Jay
UWA
Geophysics Program
AK-50,
University of Washington
Seattle, WA 98195
(206) 685-8045

Regulatory
Jerry Johns
SWRCB
Division of Water Rights
P.O. Box 2000
Sacramento, CA 95810
(916) 657-95810

Zooplankton/ETZ
Wim Kimmerer
Biosystems
3152 Paradise Drive
Building 39
Tiburon, CA 94920
(415) 435-0399

Policy/Biology
John Krautkraemer
EDF
5655 College Avenue
Suite 304
Oakland, CA 94618
(415) 658-8008

Technical/Policy
B.J. Miller
SWC
P.O. Box 5995
Berkeley, CA 94705
(415) 644-1811

Fish larva/smelt/bass
Lee Miller
CADFG
4001 North Wilson Way
Stockton, CA 95205
(209) 466-4421

Hydrodynamics
Steven Monismith
Stanford University
Dept. of Civil Engineering
Stanford, CA 94305-4020
(415) 723-4764

Fisheries
Peter Moyle
UCD
Dept. of Wildlife & Fisheries
Davis, CA 95616
(916) 752-6586

Benthos/estuarine
Frederic Nichols
USGS
MS-472
345 Middlefield Road
Menlo Park, CA 94025
(415) 329-4411

Chemistry
David H. Peterson
USGS
MS-496
345 Middlefield Road
Menlo Park, CA 94025
(415) 354-3366

Bio/Hydro/Policy
Thomas Powell
UCD
Div. of Environmental Studies
Davis, CA 95616
(916) 752-1180

Food Web Dynamics
Charles Simenstad
UWA
Wetland Ecosystem Team
Fisheries Research Institute
WH-10
University of Washington
Seattle, WA 98195
(206) 543-7185

Hydrodynamics
Lawrence Smith
USGS
2800 Cottage Way
Room W-2239
Sacramento, CA 95825
(916) 978-4648

Policy
Gregory Thomas
Cronkhite Beach
Building 1055
GGNRA
Sausalito, CA 94965
(415) 331-1232

Hydrology/Hydrodynamics
Philip Williams
Consultant
Pier 35
The Embarcadero
San Francisco, CA 94133
(415) 981-8363

Technical/Policy
Leo Winternitz
SWRCB
Division of Water Rights
P.O. Box 2000
Sacramento, CA 95810
(916) 324-5751

APPENDIX C

TITLES AND AUTHORS OF BACKGROUND (WHITE) PAPERS

1. A Discussion of Issues Relevant to the Entrapment
   Zone in the San Francisco Bay Estuary
   Wim Kimmerer

2. Synopsis of Evidence Presented to the State Water
   Resources Control Board in the Bay-Delta Hearings
   on the Functioning and Benefits of the Entrapment Zone
   David Fullerton

Copies are available from the Marine Sciences Research Center upon request.

Marine Sciences Research Center
University at Stony Brook
Stony Brook, NY 11794-5000

August 30, 1991

MEMORANDUM

TO: Harry Seraydarian

FROM: Susan Hatfield

SUBJECT: San Francisco Estuary Program's technical workshop on
             flows held at the Bay Conference Center, Tiburon, CA,
             August 27-29, 1991.

Workshop participants included scientists selected for their
expertise in hydrodynamics, primary productivity and fisheries, as
well as representatives of agencies with decision-making authority
in the Estuary. In addition to participants from the San Francisco
Bay Area, scientists working in the Columbia River Estuary,
Chesapeake Bay and Long Island Sound were present. Agency
representatives were able to benefit from the first two days'
scientific discussion, and provided insight into the kinds of
information useful for decision-making on the last day of the
workshop.

The group's task was to identify and evaluate the scientific
validity of estuarine properties and phenomena to manage freshwater
inflows to protect the ecosystem of San Francisco Bay. The
position of the entrapment zone was first considered, but was
dropped in favor of salinity, as measured 1 meter above the bottom.
Salinity was considered to be a good index because: (1) it is
simple and inexpensive to measure accurately; (2) it has
environmental meaning; (3) it integrates various flow phenomena,
including river flow and exports; (4) is easily understandable to
the general public.

Workshop participants agreed that 2 ppt was a logical salinity
level for use in managing freshwater flows. 2 ppt was identified
as a meaningful salinity level in part because it is a good index
of the upstream boundary of the entrapment zone, and in part
because it is a salinity level which can unambigously represent
marine water.   In addition, participants agreed that other
ecological processes and values, such as estuarine fish and shrimp
species abundance, anadromous fish species abundance, phytoplankton
abundance, <u>Neomysis</u> abundance, tidal marsh vegetation, and
endangered/threatened species abundance, could be tied to, and thus
managed with, control of the seasonal location of 2 ppt salinity.

The participants were able to successfully develop a matrix of the
general upstream/downstream location of 2 ppt bottom salinity vs
ecological processes for the spring, but were not as successful
developing such a matrix for summer. It was clear that further
work was needed to develop matrices for other seasons, and to

refine the relationships between 2 ppt location, time, and ecological effects.

The participants also developed curves representing the general relationship between a 2 ppt location and (normalized) probability of a strong year class for a group of estuarine species. The uncertainty associated with these relationships was represented by an envelope surrounding the curve. At the most upstream location the probability of strong year classes was low, and the associated uncertainty envelope was narrow, indicating that there was no probability of a strong year class at this general location, and the year class abundance does not fluctuate widely. As the location moves farther downstream in the Estuary the curve rises, indicating that the probability of strong year classes is higher. However, the uncertainty band is wider, mainly because abundance can be very high or only moderate when flows are higher and the 2 ppt location is more downstream. There was agreement that these graphs were generally similar for all four seasons.

Within the next few months a small working group will develop and refine a family of such curves for each season, and couple salinity to flow, so that the relationships already developed for flow can be used to identify salinity/ecological effect relationships. Refinements will include an analysis of possible alternative ways of achieving each ecological effect, and a clear statement of assumptions. This information will be used by the larger group to identify the ecological costs and benefits for alternative decisions on standards, and may lead to a recommendation on the most scientifically defensible standard or set of standards.

Delta outflow was also discussed, especially because of the ongoing SWRCB EIR process and because much of the fish and invertebrate abundance data has only been analyzed in relation to delta outflow and delta export. It was agreed that delta outflow may be an additional phenomenon useful (in conjunction with salinity) for managing freshwater inflow to the Estuary. It has, however, been difficult to measure accurately. USGS has recently worked out a technique to directly measure outflow, and this technique could be used to routinely monitor outflow in addition to monitoring salinity.

By the end of October, a synopsis of the workshop will be written by Dr. J.R. Schubel, Director of the Marine Sciences Research Center at SUNY. In November, the large group will reconvene to discuss Dr. Schubel's summary of the workshop and the four-season scenarios of salinity/ecological effects relationships. These documents will be revised and submitted to SFEP's Flows Subcommittee in December.

cc: Tim Vendlinski, W-7-3
    Amy Zimpfer, W-7-3

DRAFT REPORT

AN EVALUATION OF EXISTING DATA
IN THE ENTRAPMENT ZONE OF
THE SAN FRANCISCO BAY ESTUARY

Submitted to:

Mr. George Baumli
General Manager
State Water Contractors
555 Capitol Mall, Suite 725
Sacramento, CA 95814

Submitted by:

William Kimmerer, Ph.D.
BioSystems Analysis, Inc.
3152 Paradise Drive, Building 39
Tiburon, CA 94920

May 24, 1991

J-519

TABLE OF CONTENTS

Table 1

LIST OF FIGURES

iii

EXECUTIVE SUMMARY

This report provides an analysis of the available information on the entrapment zone (EZ) of the San Francisco Bay estuary. The analysis is an attempt to synthesize the literature on this estuary with the available data; the goal is to assess the importance of the entrapment zone to the food chain of the estuary leading to early stages of striped bass and other important fish. This study has two components: a review of the literature on the entrapment zone and related issues in San Francisco Bay, and an analysis of data from the Interagency monitoring programs. The objectives of this study were to assess existing data on the characteristics of the EZ, its importance to biological production, the importance of geographic position of the EZ to production, and the possible effect of historical changes in the strength and importance of the EZ on the abundance of important organisms.

The physical phenomenon of entrapment is reasonably well understood. Entrapment of particles occurs through the interaction of current shear with the sinking of particles. The longitudinal density gradient in an estuary produces a landward-flowing, tidally averaged bottom current that underlies the seaward-flowing surface layer. Particles that sink out of the surface layer are transported back upstream by the bottom current and become trapped within this region of two-layered flow. The effectiveness of the EZ in trapping particles depends on the freshwater flow rate, with intermediate flows causing the longest particle residence time, and tides, which vertically mix the water column and tend to oppose the formation of an EZ. The EZ moves downstream during high-flow conditions and slowly upstream when flow is low.

Previous reports on the San Francisco Bay estuary demonstrate that the EZ is the site of the highest concentrations of specific phytoplankton and zooplankton in the estuary. Some phytoplankton species are trapped as are inert particles. Entrapment of phytoplankton is apparently enhanced when the EZ is downstream in Suisun Bay, and reduced when it is upstream in the Delta. Zooplankton and fish can maintain position in the EZ by moving vertically into a depth of favorable currents, but existing reports do not demonstrate convincingly that the geographic position of the EZ is important to zooplankton. EZ position may be important to Delta smelt.

Analysis of long-term monitoring data on nutrients, phytoplankton, and zooplankton reveals several pertinent facts about their dependence on the EZ. Several species appear to be "entrapment zone species," i.e. maximum abundance is in the EZ. Several of these species are more abundant when the EZ is either downstream in Suisun Bay or at intermediate positions, compared to an extreme upstream location in the Delta. The mysid shrimp *Neomysis mercedis*, in particular, is much less abundant when the EZ is upstream. The copepod *Eurytemora affinis* is significantly less abundant when the EZ is upstream only in the fall. Striped bass survival is generally higher when the EZ is in Suisun Bay. Although a reasonable mechanism has been proposed for higher phytoplankton abundance when the EZ is in Suisun Bay, the corresponding mechanisms for zooplankton and fish cannot be determined from the existing data.

Long-term declines have occurred in a number of attributes in the estuary, including both of the above zooplankton species, striped bass, Delta smelt, and phytoplankton biomass. An additional change is an increase in water clarity, but the cause of this is also unknown. Declines over the period 1972-1987 are significant but not attributable to changes in flow or position of the entrapment zone, nor do they appear related to each other. Many of these indicators declined more in 1988 than during any previous period, probably because of grazing by the recently introduced clam *Potamocorbula amurensis*

The entrapment zone is as important to the estuary as has been claimed by previous workers, although its importance to striped bass is not fully demonstrated. For maximum production of zooplankton the entrapment zone should be at least as far downstream as the confluence of the Sacramento and San Joaquin Rivers.

The existing monitoring program has provided a good database for detecting trends but has not included sufficient analytical effort to detect the changes in a timely manner, nor has it incorporated the flexibility needed to respond to changes detected. This points out an area in which the existing study program should be improved.

1.0 INTRODUCTION

For the past two decades, the Interagency Ecological Studies Program has collected data on a variety of physical, chemical, and biological variables in the San Francisco Bay estuary. These investigations have provided one of the world's longest-term records for an estuary, constituting an impressive body of information. Much has been learned from these data and from studies designed to investigate and explain patterns observed in the data. However, much of the knowledge gained in this effort is anecdotal and not fully supported by rigorous analyses of the data. For example, many scientists working in this area believe that the entrapment zone (EZ) of the estuary is important to the survival and subsequent recruitment of larval and juvenile fish and to the food chain on which they depend (e.g. Arthur and Ball 1979). Although there are reasons to believe this might be true from studies of this and other estuaries and from some findings on striped bass, this general opinion has yet to be firmly supported using the data at hand. The analysis of much of the data has been insufficient either in amount or rigor to resolve basic questions about trends and patterns in the data.

This report is an attempt to synthesize the literature on this estuary with the available data to assess the importance of the EZ to the food chain of the estuary, and especially to early life stages of important fish. This study has two components: a review of the literature on the entrapment zone and related issues in San Francisco Bay; and an analysis of data from the Interagency monitoring programs. The extensive literature on entrapment phenomena from other estuaries is outside the scope of this project, although particularly relevant reports are cited where needed.

The purpose of this report is to present an objective analysis of the existing information. This is an important step in evaluating where we are in our understanding of the ecology of the bay and of the effect of freshwater inflows. It should also prove useful in suggesting how directed research projects might reveal further detail of the effects of flows and diversions.

The objectives of this study were to assess to what extent the following questions could be answered using the monitoring data:

1) What are the characteristics of the EZ in the San Francisco Bay estuary?

2) What is the importance of the EZ to biological production?

3) How important are changes in position of the EZ to the abundance or production of the species that use the EZ?

4) Is the long-term historical decline in many of the indicators of biological production related to changes in the EZ?

In Section 2.0 I present a review of the literature relevant to the entrapment zone of the San Francisco Bay estuary. Section 3.0 describes the results of several analyses of existing data on the EZ. Section 4.0 contains a summary of our knowledge of the EZ in this estuary and presents some recommendations for future activities. A glossary of scientific terminology used in the report is presented following the Literature Cited section.

2.0 ENTRAPMENT ZONE LITERATURE REVIEW

This literature review is focused on the entrapment zone of the San Francisco Bay estuary and on an explanation of the entrapment phenomenon. References from other estuaries are introduced only where relevant to a particular point being made.

The literature on the San Francisco Bay estuary is far less extensive and thorough than those for other U.S. estuaries (e.g. Chesapeake Bay, Delaware Bay, Narragansett Bay). However, a number of key publications provide a firm basis for examining the role of the entrapment zone. These papers have resulted to a large extent from the efforts of Interagency investigators, but relatively few of the data reported are from the ongoing interagency monitoring programs. Rather, most of these studies have reported the results of special investigations conducted for particular purposes.

In addition to published literature, I included in this review several analyses that have not been published in widely available literature, but that have received considerable peer review.

2.1 GENERAL CONCEPTS

A number of terms have been used to describe the enhanced particle concentration commonly occurring in estuaries: e.g. estuarine turbidity maximum (ETM), entrapment zone, or null zone. Although these terms do not have identical meanings, they refer to related phenomena (see Glossary). Briefly, an ETM is a location of elevated turbidity due to concentration of particles. An ETM can arise through entrapment, or through other mechanisms such as wind-driven disturbance on shoals. An entrapment zone is an area where variations in flow interact with particle settling to trap particles, and a null zone is the upstream limit of tidally-averaged two-layer flow. These concepts are discussed in Section 2.2.

Since this report discusses how the EZ affects biological production, it is useful to define this and related terms (see also Glossary). Abundance (sometimes density or concentration) is the number of organisms in a functional group (e.g. phytoplankton) or population (e.g., striped bass) per spatial unit (area or volume). Note that the term "abundance index" often refers to a measure of total size of a population, i.e. summed over the area or volume of interest. Biomass is the amount of biological material in a functional group or population per unit of area or volume. It can be expressed in units of weight (wet weight, dry weight, carbon, nitrogen) or caloric content. Productivity is the rate at which a functional group or population creates additional biomass per area or volume. It is the product of biomass times the mean specific growth rate of the organisms in the group (Kimmerer 1987). Production usually refers to productivity accumulated over time (e.g. 1 year), but many workers do not distinguish between production and productivity. For animals, growth rates are poorly known but vary less than biomass, so biomass or abundance can be estimated from production (Kimmerer 1987). Production of phytoplankton in San Francisco Bay is also

readily predictable from biomass, light, and water clarity, since nutrients are rarely limiting (Cole and Cloern 1984).

A further note regarding productivity is warranted. Like other ecological terms, this term has been borrowed from common usage to apply to a specific ecological variable. However, it carries with it the positive connotations of its common usage. These connotations are unwarranted, however, since high productivity in an ecological system is not necessarily good. The productivity of microorganisms in San Francisco Bay may have been higher when raw sewage was being dumped into the bay than now, but nobody would argue that the bay was in better condition. High production of fish or other harvestable species, usually a benefit to humans, is not necessarily related closely to high production of phytoplankton.

Salinity is used in this and other reports as an index of relative position in the estuary. Salinity is commonly expressed in parts per thousand, but the correct expression of salinity using the Practical Salinity Scale (UNESCO, 1981) is unitless, being based strictly on conductivity and temperature. The Interagency monitoring programs routinely measure specific conductance corrected to 25°C, from which salinity can be calculated if all of the salt comes from seawater. The advantage of doing this instead of expressing salt content as specific conductance is that the salinity value is a direct measure of the degree of dilution of seawater with freshwater. This is useful in considering the loss of substances from the estuary by mixing and dilution. However, salinity is not as useful when the salt content comes from other sources such as agricultural drainage, as in the eastern and southern Delta. Throughout this report I express salinity without units, and where appropriate add specific conductance values for reference, since many of the existing reports show only specific conductance.

2.2 THE PHYSICS OF ENTRAPMENT

The entrapment phenomenon is well known from a number of estuaries, and the basic concepts have been understood since 1955 (Postma and Kalle 1955). A number of publications have addressed the physics of entrapment; the following description relies heavily on the detailed (if rather technical) discussions of estuarine circulation by Jay and Smith (1990a, b).

The concept of entrapment can be understood by considering a hypothetical estuary in which the relative magnitudes of river flow, tidal flow, and friction are varied. If tidal flow is negligible, and letting friction between layers be zero for the moment, river flow enters the estuary and disperses as a surface layer of freshwater (Figure 1a). This surface layer decreases in thickness with distance from the river, but without friction no mixing occurs. The halocline, the surface separating the layers of fresh and salt water, is tilted down toward land to balance exactly the hydrostatic pressure exerted by the landward thickening of the freshwater layer. Freshwater flows seaward due to the slope in surface elevation; however, no motion would occur in the seawater layer since the forces are in balance.

In a real estuary, the shear between the freshwater layer and the seawater layer produces turbulence near the halocline, which mixes fresh and seawater across the halocline. The surface layer becomes progressively saltier toward the sea (Figure 1b). Since this layer is flowing seaward, it carries salt out of the estuary, so to conserve mass an equal amount of salt must come inward in the lower layer. This occurs because of the horizontal density gradient which causes dense seawater to flow toward less dense water nearer land. This circulation is referred to as "gravitational circulation", because the force of gravity acts on the surface slope to cause seaward flow of water at the surface, and on the density gradient to cause landward flow of bottom water.

Tidal flow is an important flow phenomenon in most estuaries. In our hypothetical estuary, gradually increasing tidal flow and decreasing river flow do several things (Figure 1c). First, tidal flow across the bottom introduces additional shear, resulting in another source of turbulent energy for mixing. Second, tidal currents can override gravitational flows, resulting in unidirectional currents at all depths. Third, tidally generated turbulence can obliterate the vertical density gradient. And fourth, increasing tidal relative to river flow moves the entrapment zone upstream (Peterson et al. 1975).

In a real estuary, strong river flow and weak (i.e. neap) tidal flow result in a configuration like that described in Figure 1b, where the two-layer flow exists at least in part of the estuary. As tidal flows increase, stratification breaks down because of increasing turbulence due to shear at the bottom (Figure 1c). Tidal velocities override first the bottom density current and then the surface current, so that at any time the flows are unidirectional at all depths. An ebb-flood asymmetry in vertical velocity profiles (Figure 2) is produced by the horizontal density gradient; that is, gravitational circulation reinforces the flood near the bottom and the ebb at the surface. This produces a tidally-averaged two-layer flow similar in its effect to that seen in the high-flow condition. The principal differences are that turbulence within the entrapment zone is greater, residence times of particles are shorter, and stratification is reduced or eliminated.

Entrapment occurs in this two-layer flow as depicted schematically in Figure 3 (Arthur and Ball 1980). Particles sinking out of the surface water become entrained in the deeper current and are carried back upstream. Near the landward margin of this region of two-layer flow, turbulent mixing or a net upward movement prevents the settlement of particles having a certain range of settling velocities, and these become trapped in the region. Between the two layers is a "plane of no net motion" at which no net landward or seaward velocity exists. Where the upstream edge of this plane intersects the bottom, two-layer flow ceases and all of the flow is seaward; this point, referred to as the "null zone", is closely associated with the EZ.

An additional mechanism of entrapment has more to do with longitudinal than vertical variation in current velocities. In most estuaries including the San Francisco Bay estuary, the cross-sectional area increases in a downstream direction (Peterson et al. 1975). River flow averaged across the estuary had a lower velocity where the cross-sectional area is larger. In addition, tidal currents generally decrease from the mouth of the estuary to some

upstream point where they vanish. The combined tidal and river velocities therefore have a minimum at some intermediate point. This minimum results in settlement of particles during slack water and subsequent resuspension during tidal flows, causing a turbidity maximum near the area of minimum current velocities (Peterson et al. 1975).

2.3 THE ENTRAPMENT ZONE IN THE SAN FRANCISCO BAY ESTUARY

In the San Francisco Bay estuary, the position and strength of the EZ is regulated by the interaction of tides and river flow, with wind increasing mixing in shallow waters (Peterson et al. 1975, Arthur and Ball 1979, Smith and Cheng 1987). The position of the tidally-averaged null zone varies from about 20 km from the Golden Gate Bridge (GGB) at a Delta outflow of 2000 m^3/s (70,000 cfs) to 80 km (about the mouth of the San Joaquin River) at 100 m^3/s (3,500 cfs; Peterson et al. 1975). This movement of the null zone occurs because variation in river flow is much greater than variation in density-driven bottom currents. The position of a given salinity, and therefore of the EZ, also depends on the spring-neap tidal cycle in that the total volume of water in the Delta is higher during spring than neap tides (Cheng et al. 1991). Actual Delta outflow is lower for a given calculated outflow (inflow less consumption and exports) during the transition between neap and spring tides than during the spring-neap transition, so the EZ position could be expected to vary as well. In addition to these sources of variation, aperiodic variations in sea surface elevation and winds, as well as nonlinear tidal effects, can alter longitudinal circulation (Walters and Gartner 1985) and therefore EZ position.

A series of reports by Arthur and Ball (1978, 1979, 1980) discussed the location of the EZ and its biological significance. The EZ contains elevated concentrations of suspended particulate matter, phytoplankton, zooplankton including the mysid shrimp *Neomysis*, and juvenile striped bass. High tidal velocities and high freshwater outflows both result in greater resuspension of particles, enhancing turbidity within the EZ. The lowest concentrations of suspended solids, phytoplankton, zooplankton, and juvenile bass occurred in the drought of 1976-77, when the EZ was furthest upstream (Arthur and Ball 1979).

Based on the distribution of suspended particulate matter over a wide range of flows and tides, Arthur and Ball (1978) stated that the EZ occurred over a surface salinity range of 1-6 (Specific conductance of 2-10 mS/cm). This agrees with the location of the null zone reported by Peterson et al. (1975).

The U.S. Geological Survey (USGS) and the U.S. Bureau of Reclamation (USBR) have measured vertical profiles of currents, salinity, temperature, and light transmission (as a measure of particle concentration) along transects up the bay starting in 1985. Unfortunately, these data have not yet been fully analyzed. Preliminary analysis of a few profiles shows entrapment of particles at a surface salinity around 1-6 (Rapp et al. 1986, Hachmeister 1987). These profiles also illustrate the effect of flow and of the spring-neap tidal cycle on stratification; high flows push the salinity intrusion downstream and enhance stratification, while spring tides tend to eliminate stratification. In addition, the current

profiles illustrate the ebb-flood asymmetry under moderate flow conditions, and two-layer flow when freshwater outflow is high.

2.4 BIOLOGICAL SIGNIFICANCE OF THE ENTRAPMENT ZONE

The EZ could be significant biologically in two ways. First, it can provide habitat for "entrapment zone species", i.e. species that are most abundant within or near the EZ. Second, as a location of elevated biomass and therefore productivity of lower trophic levels, it could serve as a source region for food for consumer species such as fish. Two issues are relevant to this discussion: the importance of the entrapment zone to various species in and near the EZ; and the importance of the geographic position of the EZ to productivity within the EZ.

A related issue is the historical decline in many of the species and functional groups in the estuary. This is related because the declines could be associated with historical changes in EZ position. Declines have been noted in phytoplankton (Orsi and Mecum 1986, Arthur 1987), zooplankton (Orsi and Mecum 1986), striped bass (Stevens et al. 1985), and Delta smelt (Moyle et al. in prep).

2.4.1 Phytoplankton, Bacteria, and Particulate Matter

Arthur and Ball (1978, 1979, 1980) showed that abundances of phytoplankton, zooplankton, and young striped bass are elevated in the EZ relative to other locations. In addition, they showed that the biomass of phytoplankton is higher when the EZ is in Suisun Bay rather than further upstream. In 1978 manipulation of flows to keep the EZ within Suisun Bay apparently resulted in high concentrations of phytoplankton, particularly relatively large diatoms. Settling rates of the most abundant diatom species were equal to the theoretical upward velocity in the EZ determined by a numerical model; this suggested that these species were being trapped within the EZ (Arthur and Ball 1980). In addition, the ratio of chlorophyll to total pigments (i.e., chlorophyll plus its breakdown products) was highest near the bottom first downstream of the EZ, indicating a greater proportion of healthy, growing cells (Ball and Arthur 1979).

Arthur and Ball (1980) presented a theory to explain the elevation of phytoplankton biomass when the EZ was in Suisun Bay. This model was expanded by Cloern et al. (1983) to include an analysis of the effects of mixing between shallow and deep locations. I refer to their explanation as the ABC model. According to this model, phytoplankton are generally light limited and therefore unable to maintain positive net production in the deep channels, where turbidity reduces the light below that needed for high rates of photosynthesis. Production is high on the shoals, however, which are extensive in Suisun Bay. When the EZ is in Suisun Bay, particles including phytoplankton are trapped by the estuarine circulation, but tidal exchange mixes phytoplankton between the shoals and the deep channels. Therefore the average growth rate of phytoplankton in this area is high, resulting in high biomass and productivity. In the Delta, most of the channels are narrow and deep with

relatively little shoal area. Thus, according to the ABC model, average growth rate of the phytoplankton is lower when the EZ is upstream, and less biomass builds up.

Cloern et al. (1983) showed that the proportion of large phytoplankton (those larger than about 20μm) in total chlorophyll, and the abundance of large diatoms, were highest when the EZ was in Suisun Bay. They also showed that the growth rate of phytoplankton in the shoals was about 10-fold that in the deep channels, owing mainly to a lack of light penetration in the deep waters. Nutrients do not limit the growth of phytoplankton, at least until biomass reaches extremely high levels during summer blooms (Cloern et al. 1983).

Several alternatives to the ABC model cannot be eliminated. The upstream or downstream movement of the EZ is caused mainly by changes in freshwater inflow, which also influences the strength of bottom currents and therefore the ability of the EZ to trap diatoms of a particular settling velocity. It is not clear whether the high phytoplankton biomass results from the postulated mechanism or simply from changes in the strength of entrapment. Furthermore, low biomass during droughts could be due to increased benthic grazing resulting from the landward penetration of marine benthic grazers (Nichols et al. 1990). However, the ABC model is the most consistent explanation of the low biomass when the EZ is upstream.

Much less information is available on the detrital and bacterial components of particulate matter. The nutritive value of particles, defined as the ratio of protein to carbohydrate, was higher in the EZ than elsewhere (Barclay 1981). The ratio of nutritionally useful materials to total particulate matter did not vary with sampling station, suggesting a similar mechanism for entrapment of nutritional and total particles (Barclay 1981).

The production of bacterioplankton in Suisun Bay during 1988 was 5 times higher than phytoplankton production, implying important sources of organic matter not associated with phytoplankton (Hollibaugh and Wong 1990). Whether this organic matter comes from the rivers is unknown. However, this organic matter could provide alternative food for zooplankton and other herbivores.

2.4.2 Zooplankton

A number of papers have been prepared on the abundance of various zooplankton species in relation to the EZ. The copepod *Eurytemora affinis* and the mysid *Neomysis mercedis* both appear to be entrapment zone species (Heubach 1969, Siegfried et al. 1979, Orsi and Knutson 1979, Knutson and Orsi 1983, Orsi and Mecum 1986). *E. affinis* is the most abundant species of mesozooplankton in the lower salinity zones of estuaries on both the east and west coasts of the U.S. and Europe (e.g. Heinle and Flemer 1975, Burkill and Kendall 1982, Miller 1983, Orsi and Mecum 1986). Both species are important food for larval striped bass, *E. affinis* in the first few mm of growth and *N. mercedis* after the bass reach 10-14 mm length (DFG 1988b). Delta smelt also consume these species (Moyle et al. in prep.). The copepod *Sinocalanus doerrii*, introduced around 1978, is most abundant upstream of the entrapment zone (Orsi et al. 1983). A more recent introduction,

Pseudodiaptomus forbesi, took up a position similar to that of *E. affinis* in 1988 (Orsi and Walter 1991).

Both common entrapment zone species, *E. affinis* and *N. mercedis*, are most abundant in the entrapment zone, and both have declined substantially over the duration of the sampling program (Knutson and Orsi 1983, Orsi and Mecum 1986). Causes of declines have not been determined, although the introduction of *Sinocalanus* has been identified as a possible cause of the decline in abundance of *Eurytemora*.

Neomysis mercedis has a peak in abundance at a salinity around 2-3, close to the defined upstream end of the entrapment zone (Knutson and Orsi 1983). It is believed to maintain position in relation to the entrapment zone by the interaction of its vertical position with the estuarine circulation rather than through direct effects of salinity (Heubach 1969, Siegfried et al. 1979). Abundance indices, which are estimates of the total population size, were higher when the EZ was in Suisun Bay than when it was upstream (Siegfried et al. 1979, Knutson and Orsi 1983). It was postulated that this was due to a reduction in habitat size owing to the restricted channels in the Delta (Siegfried et al. 1979, Knutson and Orsi 1983). In addition, Knutson and Orsi (1983) stated that cross-Delta flows rendered the eastern and southern Delta unsuitable as habitat for *N. mercedis*, although it is not clear how this could happen. It is also not clear whether abundance indices were lower when the EZ was in the Delta because of reduced habitat size alone, or whether there was also a reduction in abundance (i.e. number per cubic meter) within the EZ.

There is no evidence in any of these studies that reproductive or growth rates of zooplankton are different in and out of the EZ. Therefore production of entrapment zone species of zooplankton is probably higher in the EZ owing to the higher biomass.

In one respect the studies cited above made a significant error in analysis of the data. For the most part the data were related to fixed stations rather than to salinity, and no account was taken of the salinity variation in calculating means or correlations between species. This resulted in some possibly spurious results. For example, significant correlations were noted between *Neomysis* at certain stations and flow (Siegfried et al. 1979), between *Neomysis* and *Eurytemora* (Knutson and Orsi 1983), and between zooplankton abundance and chlorophyll (Orsi and Mecum 1986). Since chlorophyll and many zooplankton species have similar spatial distributions, and since the EZ and the abundance peak move up or downstream depending on freshwater flow, these correlations can arise through movement of the entrapment zone. This issue is discussed further in Section 3.5.3.

2.4.3 Striped Bass

Striped bass (*Morone saxatilis*) range throughout the estuary and lower rivers but are concentrated in the low-salinity region of the estuary during early life (DFG 1988b). This may not be considered an "entrapment zone species", since all life stages are found well upstream and downstream of the entrapment zone. However, it is most abundant near the entrapment zone during larval and early juvenile development (Arthur and Ball 1980, DFG

1988b). Furthermore, Fujimura (1990) has found that bass eggs are most abundant near the surface but that larvae tend to be more abundant away from the surface. To that extent that an entrapment zone is present, this behavior would result in transport of eggs by river flow to the entrapment zone, followed by retention of the bass in that area. Hatching and development of larvae before they reach the EZ could result in delayed transport because of reduced flow at depth, which may explain the tendency for the majority of the larvae to be found upstream of the EZ (DFG 1988b).

Recently, a good deal of attention has been paid to the long-term decline in striped bass in this estuary (Stevens et al. 1985). The prevailing view of DFG scientists (Stevens et al. 1990a) is that the decline was caused by reduction in young-of-the-year (YOY) through direct removal by the project pumps, resulting in lower adult abundance and consequently reduced egg abundance. With the normally low survival of fish through egg and larval stages, reduced egg abundance causes a further reduction in YOY.

The argument of Stevens et al. (1990a) is as follows. Increased exports in the early 1970s resulted in poor survival of young bass, with an estimated removal of 31-84% in the late 1980s. This decline occurred primarily in the Delta (rather than in Suisun Bay). The resulting decline in recruitment produced a reduction in adult stocks, with concomitant lowering of egg production. The most plausible alternative explanation of the decline is that survival of early bass larvae is lower than it used to be because of the decline in zooplankton abundance. However, there is no evidence that survival of early larvae has declined, and the ratios of YOY to egg indices do not reveal a strong trend (Stevens et al. 1990a). Variation in survival of early larvae may explain the dependence of YOY on flow in the estuary, but not the long-term decline. Growth rates of larvae measured since 1984 are variable between years, and this variation could be due to changes in food supply (Miller 1990), although starved larvae are rare or absent from the estuary (Bennett et al. 1990).

The DFG report includes a quantitative analysis of the removal of striped bass by the pumps and of the effect of declining adult stocks on YOY. However, it fails to account for evident effects of toxicity on both young (Foe 1990) and adult (Nishioka 1991) bass. In addition, the increase in adult mortality over the last decades (DFG 1988a) could also lead to lower egg production. Although the DFG report is quantitative in testing hypotheses using empirical relationships, no mathematical model is presented to support the analysis outlined above. In the absence of such a model, it is difficult to separate the effects of reduced egg production and mortality at various life stages. Furthermore, the analysis fails to explain why long-term declines in survival of YOY would not be reflected in similar declines in survival of the larvae, which are found in fresher water and should be more vulnerable to pumping.

A contrary view presented by J. Turner (1990) is that years of high YOY index (e.g. 1986) occur when eggs and larvae from the San Joaquin spawning area are washed into the EZ because of relatively high flows in the San Joaquin. The underlying assumption is that eggs spawned in the Sacramento River do not contribute as much to the population. Although Turner's model may be a good explanation of the relatively high YOY index of 1986, it does not explain why indices were consistently higher before 1977 than after.

2.4.4 Delta Smelt

Interest in Delta smelt (*Hypomesus transpacificus*) has grown recently with petitions to State and Federal agencies to list it as an endangered species. Two recent reports (Stevens et al. 1990b, Moyle et al. in prep) provide a complete analysis of current data indicating the status of this species. Apparently this species is concentrated in the entrapment zone at least during larval development. Of the seven independent programs that sample for abundance of Delta smelt, all indicate a decline in abundance in the early to mid 1980s, but the timing is not the same in all studies. Moyle et al. (in prep.) propose that the decline may be caused by upstream location of the entrapment zone, since the EZ has been upstream of Suisun Bay in every year since 1983 except for 1986. However, only two of the seven studies show a high abundance in 1982-83, and only one shows moderate abundance in 1986, the three years in the 1980s with the highest springtime freshwater inflows.

2.5 EVALUATION OF THE CURRENT STATE OF KNOWLEDGE

Little has been published on the biological activity of the EZ in the last 8 years, although several data summaries, including some information on the EZ, were presented to the State Water Resources Control Board in 1987-88 (Arthur 1987; DFG 1988a,b). Either the subject is believed to be well enough understood that no further information is needed, or the subject has not been pursued because of changing agency priorities.

The early reports on EZ position focused almost entirely on the phytoplankton. The analyses (Arthur and Ball 1980, Cloern et al. 1983) are reasonably convincing in that they offer the most parsimonious explanation of the observations. However, these analyses do not rule out other explanations of high phytoplankton biomass when the EZ is in Suisun Bay, such as the generally stronger two-layer flow (Cloern et al. 1983). No further analysis has apparently been conducted on this.

A common assumption is that, since the food chain depends on phytoplankton, what enhances phytoplankton must also enhance zooplankton and larval (and therefore presumably adult) fish. This link has not been established beyond a simple correlation of long-term trends (Orsi and Mecum 1986). Since these trends could be due to other changes, the correlations do not establish cause. Furthermore, it is very likely that at least some EZ species (especially *Eurytemora*) may depend as much on organic detritus as on phytoplankton (Heinle et al. 1977).

In fact, there is some evidence that the long-term declines in zooplankton and striped bass are not due to changes in phytoplankton. First, limited experimental data (Kimmerer 1990) showed no evidence of food limitation of *Eurytemora affinis*, which was the most abundant zooplankton species in the estuary. If food is not limiting the growth or reproduction of this species, then changes in phytoplankton will not be reflected in changes in abundance of *Eurytemora*. Second, the recent analysis of the decline in striped bass (Stevens et al. 1990a) discounts the importance of the food web in regulating the population size of bass (See Section 2.4.3).

To summarize, the published and unpublished analyses to date show evidence that the existence of the EZ is important to phytoplankton, some zooplankton, and possibly Delta smelt. The position of the EZ has been shown to be important to phytoplankton, and a reasonable mechanism has been proposed. However, analysis of its importance to higher trophic levels has depended on the link between phytoplankton, zooplankton, and fish, which has not been established quantitatively.

3.0 DATA ANALYSIS

This section describes the analyses performed on existing data obtained primarily from the Interagency Monitoring Programs (Figure 4). Results are interpreted and compared with previous analyses in section 4.0. Zooplankton data, along with ancillary data such as surface conductance, chlorophyll, and Secchi disk depth, were obtained from DFG. This data set includes samples taken at 81 stations between 1972 (1976 for chlorophyll) and 1988, mainly during March to November, all at or near high tide. Because of that consistency, and because of the large number of stations, I have used those data wherever possible to describe the distribution of salt and particulate matter in the estuary. Data on chlorophyll, phytoplankton abundance, nutrient concentrations, and turbidity were obtained from data collected by the Department of Water Resources (DWR data set) from 1968 (1975 for phytoplankton abundance) to 1989. Stations in the Southeastern Delta were excluded, leaving a total of 16 stations. Nearly all of the DFG and DWR data were from samples taken near the surface, except for zooplankton samples which were oblique tows. Data from the DFG egg and larval survey were also used to examine the potential effect of the EZ and its position on striped bass eggs and larvae.

Inflows and exports were obtained from monthly output of the DWR DAYFLOW accounting program. These data include measured flows into the Delta, estimates of minor flows to obtain total inflows, estimates of net consumption within the Delta, and measured export flows at the State and Federal projects. Net outflow is calculated by difference. Although these values have been criticized on the basis that they do not include tidal effects, the use of monthly means largely eliminates that problem. The effect of the spring-neap tidal cycle on position of the EZ is discussed in Section 3.2.2. Uncertainty in net Delta consumption introduces some error to net outflow calculations.

3.1 ANALYTICAL APPROACH

The principles used to guide the data analysis were: 1) Use all of the relevant data rather than breaking them up into smaller segments; 2) Account for known sources of variance such as salinity to permit more powerful analyses of other sources of variance; and 3) Use data that are consistent in time and space.

I believe that many previous analyses of data from the estuary have been hampered by referring the data to fixed sampling stations. Tidal excursions and changes in river flow cause the EZ to move longitudinally within the estuary at time scales from hours to months. Since the salinity distribution moves more or less in concert with the EZ, data on the EZ were analyzed in reference to salinity rather than to fixed stations. Section 3.2.2 discusses potential problems in using surface salinity to represent EZ position. In sections 3.4 and 3.5.3, geographic position of the EZ is also brought into the discussion as a separate variable to estimate its effect.

Another reason for referring all measurements to salinity is that this is the single most important variable affecting species composition at any point in the estuary (e.g. Miller 1983). Each estuarine species has an optimum salinity range, and most species fail to survive at salinities well outside that range. Thus much of the spatial variability in abundance of a given species can be explained simply on the basis of salinity. On the basis of salinity alone, one would expect to find estuarine species to have high abundance near the salinity optimum and lower abundance elsewhere (e.g. Miller 1983). By removing or accounting for the effect of salinity as a known factor, we can obtain improved descriptions of other sources of variation. Furthermore, by removing the effects of salinity and, perhaps, season, we can determine whether correlations among species or trophic levels (Orsi and Mecum 1986) are due to salinity effects or to ecological interactions.

The majority of observations in the DFG data set (around 14,000 records) were obtained at low rather than high salinities. To analyze effects of salinity in this large data set required a simplifying model. Instead of fitting an assumed salinity distribution to the data, I divided the salinity range into 20 classes containing roughly equal numbers of observations. Using equal observations gives approximately equal confidence intervals in all classes, avoiding the statistical problems that occur when the classes at one end of the distribution contain few observations. However, the salinity classes contain different salinity ranges (Table 1), and graphical displays are distorted. In several graphs in following sections, the mean salinity in each class is used to eliminate this distortion.

The general objective of this analysis was to extract underlying patterns from the existing data. Often these patterns are obscured by effects such as salinity, as outlined above, or season. To eliminate these factors while retaining as much of the full data set as possible for analysis, I calculated anomaly values for many of the variables. An anomaly is the deviation of a particular datum from the mean of all data within some range. In the case of salinity, I took the mean of all data within each salinity class and subtracted it from each observation in that class. This resulted in an anomaly representing the deviation of that individual value from the mean. Most of the variance remaining in anomaly values is due to causes other than salinity (the slight variance due to differences in salinity within classes is not removed and appears as error variance). This approach is useful in determining long-term trends or spatial patterns, which could be obscured by variation in salinity among stations. In addition to anomalies by salinity class, I also used anomalies by month to eliminate the average seasonal trend represented by monthly means.

The zooplankton abundance data were log-transformed before analysis so that various statistical procedures could be performed. This is a common practice in analyzing abundance data, in which the variance is correlated with the mean, rendering commonly used statistical procedures invalid unless the data are transformed. Log transformation alters the structure of the variance so that changes by a given factor, say 2, are represented the same no matter what the base value. That is, a change in abundance from 1 to 2 has the same influence (and appearance on a graph) as a change from 1000 to 2000. This makes sense biologically because populations grow exponentially in the absence of resource limitation; that is, they change by multiples.

A drawback to log transformation is that zeros cannot be transformed. I dealt with this problem by adding a constant to all values before transformation. The choice of the value to add can affect results of the analysis. I chose the added value to be a power of 10 close to the minimum non-zero values obtained. In other words, I assumed that a zero value was not zero but just below the detection limit. The value added was 10 for copepods and 0.1 for *Neomysis*.

The DFG zooplankton data set contained a number of observations from stations or times of year not represented consistently throughout the period of record. For example, some stations were sampled only during a few years of the study; also, samples were taken in winter only in the first few years. To make the data set more consistent and thereby to reduce bias, I extracted a core data set containing samples taken at 35 stations in March-November of each year. I also eliminated samples for which salinity data were not taken. The resulting data set contained 9597 observations. For some purposes I added back downstream stations (San Pablo Bay) sampled only during high-flow periods, since the core data set did not extend far enough downstream at those times.

Details of data preparation and analysis peculiar to each data set are discussed below along with the results of each analysis.

3.2 PHYSICAL CHARACTERISTICS

The characteristics discussed here include flow conditions as described by the DAYFLOW variables, location of the EZ, and its dependence on flow. The data used to define location of the EZ included specific conductance and Secchi disk depth from the DFG data set.

3.2.1 Flow Conditions

In this section I discuss historical patterns in freshwater flow to set the stage for a later analysis of possible causes of changes in the ecology of the entrapment zone and some of its species. Since flow affects entrapment zone position (Peterson et al. 1975), understanding changes in flow is essential to understanding this segment of the estuary.

An increasing trend exists in the data for export flows but not for Delta outflow. Figure 5 shows the historical trend in the anomaly (monthly pattern removed) of Delta outflow over the period for which we have zooplankton data (1972-1988). Although there are large interannual differences, no general trend in outflow is apparent over this period. Export flows, however, have increased over this period (Figure 6) by about 3000 cfs, but the percent of inflow exported reflects the cyclic pattern in outflow more than the trend in exports (Figure 7). The upward trend in export flow is statistically significant (linear regression, $p < 0.001$). The trend in percent exports is not quite significant ($0.05 < p < 0.1$), partly because of the large variations of outflow, and partly because inflows are varied to provide water for exports (Arthur 1987).

When the above data are grouped by season, different trends emerge. Interannual differences in percent export flow are greatest in fall and winter (Figure 8) and lower in spring and summer (Figure 9). The only time period for which a significant increasing trend exists over the period 1972-1989 is the fall ($p < 0.05$, linear regression). Seasonally, export flows and percent exports are highest in summer and lowest in winter.

3.2.2 Location of the Entrapment Zone

This section presents support for the use of a fixed salinity or specific conductance as an operational definition of the position of the EZ. The EZ is defined as the location where particles are concentrated by the action of circulation patterns. A clear indication of the location of the entrapment zone would require the measurement or calculation of net flow velocities as a function of position in the estuary. These measurements have been made only a handful of times (Peterson et al. 1975; Hachmeister 1987), so an operational definition of EZ position is required. This could be based on the location of the turbidity maximum, or on a particular salinity value.

Arthur and Ball (1978) used 2 mS/cm surface specific conductance (at 25°C), corresponding to a salinity of about 1.2, as an operational definition of the upstream end of the EZ. Since surface conductance is measured routinely in all of the Interagency monitoring programs, this allows comparisons among different programs. The principal drawbacks of the definition of the EZ by surface conductance are that this does not take stratification into account, and that the EZ may not always maintain the same spatial relationship to the salinity distribution.

Since turbidity is also routinely measured as Secchi disk depth, a turbidity maximum would seem to provide an operational definition more closely related to the actual phenomenon of entrapment than salinity. However, several problems arise in using this definition. First, turbidity maxima can arise in the absence of entrapment (Section 2.2). Second, a Secchi disk permits the measurement of surface turbidity only; turbidity in the lower part of the water column may not be easily related to turbidity at the surface (e.g., see Arthur and Ball, 1979 Fig. 10). In addition, the position of the EZ determined with a Secchi disk depends on differences among stations in a rather crude and somewhat subjective measure of light penetration.

Defining the EZ using surface salinity has the advantage of simplicity, in that a single measurement suffices to determine whether a station is in the (defined) EZ or not. It also has a basis in physics: entrapment can occur only where density-driven circulation exists due to a horizontal salinity gradient. Since this can occur only where salinity is measurable, its upstream edge must be fairly close to the 2mS/cm point. Furthermore, it is useful as a relative measure, since the EZ position can vary widely within the estuary but only slightly relative to the salinity distribution (Peterson et al. 1975).

I determined the approximate position of the EZ by the operational definition from monthly mean data on specific conductance at each station in the DFG zooplankton core data set plus the downstream stations. First I calculated a smoothed value for specific conductance

every 2 km of distance from the Golden Gate Bridge between 60 and 120 km. The position of the EZ was determined as the point where conductance was closest to 2 mS/cm. In months of high flows the EZ was out of the sampling area, so these months were dropped.

I used Secchi disk depths to indicate how the turbidity maximum deviates from the location of the ZMS/cm point. The long-term average position of the turbidity maximum occurs in salinity classes 13-17, corresponding to a salinity range of 1.2-6 (Figure 11).

To determine how the turbidity maximum varied with EZ position, scatter plots of Secchi disk depth vs. salinity class (DWR data set) were examined for each month in the record, and the salinity class at which the minimum occurred was noted. These data were converted to position using plots of salinity vs. position, and are plotted against location of the EZ as defined above (Figure 12). The turbidity maximum moves an average of 8 km relative to the operationally defined EZ position as that position shifts from 65 to 95 km from the Golden Gate Bridge. That is, the mean difference between the turbidity maximum and the position of 2mS/cm surface salinity is positive when both are upstream in the Delta, and slightly negative when both are downstream in Suisun Bay. This is because of the relationship of EZ position and flow (Peterson et al. 1975; see below). As flow increases, pushing the EZ downstream, stratification also increases, so that the difference between surface and bottom salinity increases (Arthur 1987). Since entrapment occurs over a range of salinities throughout the water column, the salinity of surface water overlying the EZ is lower when stratification is strong (and flow is high). Figure 12 indirectly illustrates the discrepancy between surface salinity and the salinity defining the EZ. However, the scatter in these data is large, mainly because of uncertainty in determining the point of minimum Secchi disk depth. The relationship is monotonic, meaning that the operational definition provides an unambiguous index of EZ position (i.e., 2 mS/cm)

EZ position by the operational definition moves downstream with increasing flow (Figure 13; see also Peterson et al. 1975, Arthur and Ball 1980, Arthur 1987). The rather wide range of EZ positions for a given flow occur because I used monthly values from DAYFLOW, ignored tidal effects, and ignored the fact that EZ position moves downstream on increasing flows faster than it moves upstream when flow decreases (Peterson et al. 1975). Plotting the time trend in EZ position illustrates how the EZ has moved between the Delta and Suisun Bay (Figure 14). As with outflow, no historical trend is apparent in EZ position. This is confirmed by analysis of the anomalies in EZ position with monthly variation removed, which also shows considerable interannual variability but no long-term trend (Figure 15). There is no significant long-term trend in the anomaly data, whether by year, month, or season (p>0.1, linear regression). Therefore long-term trends in biomass or abundance over the period 1972-1988 cannot be attributed to changes in EZ position, regardless of any correlations.

A number of authors have referred to the decrease in habitat volume as the EZ moves from Suisun Bay into the Delta (Siegfried et al. 1969, Knutson and Orsi 1983). I calculated the approximate volume of water in the EZ by integrating the cross-sectional area from Peterson et al. (1975, Figure 4) between salinity values of 1-6 for each month in which EZ position

data were available. The resulting relationship (Figure 16) clearly shows that EZ volume is lower when the EZ is in the Delta. This comes about mainly because of the decrease in cross-sectional area with distance upstream into the Delta.

3.2.3 Temperature and Transparency

Temperature anomalies show a slight but significant increase over the period 1968-1990 in the DWR data (Figure 10; $p < 0.05$, linear regression), but not in the DFG data ($p > 0.1$). This may be partly because the DFG data did not include 1968-71, when the DWR temperatures were low, or 1989 and 1990 (because of the longer processing time for the DFG data) when temperatures were high.

Transparency has increased in the system: anomaly values for turbidity as 1/Secchi disk depth (DWR data set) have decreased significantly ($p < 0.01$, linear regression of annual means, Figure 17). This is in contrast to the report of Arthur (1987), who stated that the historical change in transparency in Suisun Bay could be accounted for by movement of the EZ and river flow.

3.3 CHEMICAL CHARACTERISTICS

This section discusses concentrations and inputs of nutrient elements and organic matter and briefly addresses toxic materials. Oxygen is not considered, since it is always near saturation in and around the EZ (Arthur 1987). These data were obtained from the DWR data set from 1968 to 1990. However, coverage was rather thin in the early years. Most of the nutrients vary substantially with salinity and season, so a small number of samples in a given year could seriously bias the annual mean. Therefore, I excluded years before 1971 from this analysis.

The nutrients considered here include nitrate plus nitrite, ammonium, ortho-phosphate, and silicate. Of the two forms of nitrogen, nitrate and nitrite (together) are more important components of stream water, while ammonium is representative of sewage input and recycling within the estuary. Phosphorus can come from either source, while silicate, derived almost entirely from weathering of rocks, enters in stream water.

Nutrients apparently limit phytoplankton growth only during the maximum summer phytoplankton bloom, if at all (Cole and Cloern 1984). Therefore nutrient concentrations within the EZ provide an index of the extent to which phytoplankton could develop. If all of the major nutrients are present in excess (essentially, this means above detection limits), then something else is limiting phytoplankton biomass, usually light. Also, the relationship of nutrient concentrations to salinity gives an indication of the nonconservative reactions of these nutrients, i.e. incorporation into organic matter (Officer 1979).

The relationship of nutrients to salinity was initially determined using salinity classes as discussed above, then converted to relationships with salinity using the mean salinity in each class.

Ammonium (Figure 18) was highest in winter and lowest in summer, with a broad minimum at salinities of 0.2-10 in all seasons. This reflects either a loss of ammonium in this region or, more likely, biological processes acting to reduce the concentration of ammonium. Nitrate (Figure 19) has a sharp minimum at a salinity of 0.2 and a broad minimum during summer, but is relatively flat in other seasons. Ortho phosphate (Figure 20) was lowest at the upstream end of the range of samples, and relatively flat at other locations. However, total phosphorus had a broad maximum at intermediate salinities (in and downstream of the EZ), indicating that dissolved organic P was highest there, probably because of an overall increase in organic matter. Silica (Figure 20) declined almost linearly with salinity.

Nutrient concentration anomalies generally did not have a long term trend, except that ammonium and phosphate increased significantly ($p < 0.05$) in spring (Figures 21 to 24). These trends may reflect the decreasing phytoplankton concentrations (Section 3.4), although they may reflect improvements in analytical practices, since variability among individual data declined as well. If the early years (1971-73) are eliminated from the analyses, the trends become insignificant.

Toxic materials such as pesticides, hydrocarbons, and metals have been measured on occasion but the detection limits are too high to measure environmental concentrations reliably (Arthur 1987). Nevertheless, there is concern over the influence of toxic materials, particularly agricultural pesticides, anti-fouling chemicals, and industrial wastes. In the upper estuary the biggest problem would seem to be releases from the rice fields, which peak in mid-May (D. Wescott, Sacramento Regional Water Quality Control Board, pers. comm.). A change in crops planted, with attendant changes in pesticide application, occurred around 1976-82, coincident with some changes in estuarine biota (following sections). However, the declines seen in the crustacean zooplankton of the EZ (see Section 3.5) occurred in all months, but most steeply in summer. Thus the effect of these pesticides appears minimal, since the crustaceans appear most sensitive to pesticides (Foe 1990).

3.4 PHYTOPLANKTON

Phytoplankton abundance has been measured in two ways: as chlorophyll in both the DFG and DWR data sets and as abundances of a few common diatom species in the DWR data set. Chlorophyll $\underline{a}$ is the most commonly used measure of phytoplankton biomass, since all phytoplankton cells contain it. However, the chlorophyll per unit biomass (carbon or weight) varies widely, and there is no easy way to distinguish among the many phytoplankton species. Enough is known about phytoplankton biology to demonstrate that different species have vastly different requirements and responses to the environment. Thus chlorophyll is only a crude measure of phytoplankton abundance, but on the other hand it is easy to measure and unequivocal. Also its degradation products, known collectively as phaeopigments, are produced in digestion and can be useful as indices of herbivory. Primary production is not routinely measured but can be calculated from chlorophyll (Cole and Cloern 1984).

The two datasets for chlorophyll have similar patterns with respect to salinity if similar time periods and stations are used: when data from winter and from before 1972, and the

stations in the eastern Delta are eliminated from the DWR dataset, the results are similar to those from DFG (Figure 25). The patterns are similar, with a broad peak in salinity classes 15-18 and low values at higher salinity.

The ratio of chlorophyll to total pigment (i.e. chlorophyll plus phaeopigments) in the DWR data set was lowest in salinity classes 12 and 13, higher in the EZ, and highest in the freshwater samples (Figure 26). This difference was small, and may have occurred through lysis (disruption) of cells of freshwater algae on encountering significant salinity, since the abundance of herbivores is highest in the EZ (Section 3.5).

Chlorophyll values in both data sets have decreased over time since about 1972 (Figure 27). This decrease is statistically significant (regression, $p < 0.001$) and comes to about 10 μg Chl/l over the entire period. Phaeopigments likewise decreased, but the ratio of chlorophyll to total pigments decreased; that is, phaeopigments decreased less than chlorophyll (Figure 28). This could represent an increase in herbivory, although herbivores have, if anything, decreased (Section 3.5).

Chlorophyll anomalies with monthly means removed were used in an analysis to confirm the importance of EZ position reported by Arthur and Ball (1980) and Cloern et al. (1983). I combined the anomalies with data on position of the EZ for each month and year. The position data were divided into four categories: less than 72 km, 72-82 km, 82-92 km, and 92 km or over from the Golden Gate Bridge. The first two categories place the EZ in Suisun or Honker Bays and the last two in the western Delta. The relationships of chlorophyll to salinity class were then determined separately for each of these position categories.

The differences in chlorophyll among categories of EZ position were not as clear as previously reported, but were significant (Figure 29 <0.01, analysis of variance of data in salinity class 12-18). The means and confidence limits of chlorophyll across the broad peak (Salinity classes 14-19) show that the two intermediate EZ positions had higher mean chlorophyll concentrations than the uppermost or lowermost positions. However, in salinity classes 9-12, chlorophyll was highest when the EZ was in the most downstream position. This offers some support, on the basis of the entire time series, to the ABC model.

The cell count data are available from 1975 on. I analyzed data for only a few common diatoms since these are reported as important in the entrapment zone, and some are known to provide good food for herbivores (e.g., Cahoon, 1981).

The diatoms *Thalassiosira* sp. and *Skeletonema costatum* were most abundant when the EZ was at intermediate positions, based on monthly means (Figures 30 and 31). This provides some support with earlier findings (Arthur and Ball 1980, Cloern et al. 1983) showing that these diatoms were most abundant when the EZ was downstream, although high values occur when the EZ is as far upstream as the confluence of the Sacramento and San Joaquin Rivers. However, the operationally defined EZ position is about 5 km upstream of the

actual center of the turbidity maximum (Figure 12), so the proposed mechanism appears to hold in these data as well.

It is not surprising that the monitoring data show less effect of EZ position than data previously reported. Those data were taken in studies designed specifically to answer questions about the EZ. The monitoring program has broader objectives and is not as well suited to answering specific questions about the EZ. Many of the monitoring stations are upstream of the EZ for much of the time, and only a small number of samples are taken each month from within the EZ.

3.5 ZOOPLANKTON

The data in the DFG data set consisted of abundance (number /m^3) of adults of *Eurytemora affinis* and all sizes $\geq$ 4mm of *Neomysis mercedis*. *Neomysis* has been sampled since 1968 but for consistency with other zooplankton data we have considered only the samples taken from 1972 on. Several other species are discussed in Section 2.4.2.

3.5.1 Responses to Salinity

The distribution of any estuarine species will have a peak of abundance in a region of optimum salinity and a decline toward zero at higher and lower salinities. *Eurytemora* has a broad abundance peak at a salinity around 2 (Figure 32). The apparently steeper drop toward higher salinities is an artifact of the choice of salinity classes, since there were few classes above the peak. The corresponding distribution of geometric mean values vs. salinity (Figure 33) gives a better perspective of the response of this species to salinity but is less useful for analytical purposes, since the low-salinity end of the distribution, which contains most of the samples, is compressed to the left-hand part of the graph.

Similar plots for *Neomysis* (Figures 34 and 35) resemble those for *Eurytemora*, except that the abundance of *Neomysis* at low salinities is a greater proportion of the peak abundance than for *Eurytemora*. The abundance peaks of both species were at a salinity of 2.

Eurytemora affinis is known to have a broad tolerance to salinity from nearly 0 to about 20, with an optimum at 12, based on laboratory data (Roddie et al. 1984). *Neomysis mercedis* is found in freshwater: its name comes from Lake Merced, where it thrives, and Heubach (1969) found that rates of reproduction were highest from freshwater to a salinity of 3.6. The distributions of these species are therefore regulated not only by salinity. Other potential regulatory factors include interactions between behavior and the complex circulation of the estuary, and spatial differences in birth and mortality rates.

3.5.2 Historical Trends

To obtain a clear record of the historical trends in abundance of the entrapment zone species, anomaly values were calculated by subtracting the means for each combination of salinity class and month from the data. These anomaly values were then combined by year

to get means and confidence intervals for each annual value. Plots of these values by year (Figure 36) show that *Eurytemora* declined in the 1970s and again in 1987-88. A linear regression of annual mean abundance vs. year (through 1987) is significant ($p < 0.001$), as is a quadratic regression ($p < 0.001$). The latter gives a better fit to the data because of the apparent leveling off around 1979 (Figure 36).

The decline in 1988 cannot be tested using annual means, since there is only one point in the data set so far. Using the monthly mean anomalies gives a significant difference between 1988 and earlier years but involves some statistical constraints (the assumption of independence may be violated). Nevertheless, the difference between 1988 and previous years is exceptionally large, representing a 3-fold factor difference between 1988 and 1983, the next lowest previous year. Furthermore, data for 1989 and 1990, not yet in the data set, show that the abundance of *Eurytemora* has remained exceptionally low.

There has been some concern that the interior Delta has become less suitable habitat for young striped bass than it once was, and there is speculation that the early decline in *Eurytemora* was more severe in the Delta than in Suisun Bay. Keeping with the practice of referring the data to salinity rather than location, it is clear that the decline occurred equally throughout the system. The decline in *Eurytemora* abundance in the 1970s occurred in all salinity classes but was, if anything, steeper in the classes near the center of the abundance peak (Figure 37), and least in class 20.

In addition, it has been suggested that the decline may have been greater in spring months when striped bass larvae enter the estuary. This is also incorrect; the slope of the decline was greater in the summer and fall than in the spring (Figure 38).

The abundance of *Neomysis* was apparently higher in the first four years of the study than in 1976-87 (Figure 39; $p < 0.001$, Mann-Whitney U test using annual means). This is similar to the patterns seen for several species of freshwater zooplankton (S. Obrebski, pers. comm.). In addition, the abundance of *Neomysis* apparently declined in 1988 as compared to previous years, but was not as low as in 1977 (Figure 39).

3.5.3 Effect of Position of the EZ

The position of the EZ was determined by the operational definition (Section 3.2.2). Frequently in March and November the sampling program did not cover a sufficient range of salinities to effectively sample the EZ, so this analysis is confined to April through October. The core data set plus downstream stations were used to extend the salinity range as far as possible. Log-transformed abundance data for *Eurytemora* and *Neomysis* were combined with data on position of the EZ for each month and year. Anomalies were not used because the salinity pattern was of interest, and because the EZ is further downstream in the spring months than in the summer. The position data were divided into four categories and the analysis performed as reported in section 3.4.

3-10

The results for *Eurytemora* show a shift in peak abundance toward higher salinities, and a narrowing of the peak, when the EZ is upstream than downstream (Figure 40). There is little difference in peak abundance. In Figure 41, the long-term linear trend with years has been removed and the means of the 5 highest contiguous abundance values (i.e., the peak values) calculated by season. These peak values differ significantly among EZ positions for the fall season, with the highest values when the EZ is between 72 and 92 km from the Golden Gate Bridge. In spring, the differences are not quite significant ($0.05 < p < 0.1$), with the two highest means being those with the most downstream EZ position.

Neomysis abundances were lower when the EZ was upstream (Figure 42), but this pattern also changed by season and was correlated with temperature in some cases. Since the temperature was higher when the EZ was upstream, I calculated regressions of log *Neomysis* abundance, from the 5 contiguous salinity classes with the highest abundance as for *Eurytemora*, vs. temperature separately for each season, and used the residuals in an analysis of variance to test for differences among EZ positions. This removed the confounding effect of temperature to the extent that this effect is linear. The differences among EZ positions were significant in all cases (Figure 43, $p < 0.01$, Analysis of Variance), with the lowest values always when the EZ was above 92 KM from the Golden Gate Bridge. In spring, as for *Eurytemora*, the highest abundance was with the EZ at its furthest downstream position, while in fall *Neomysis* was about equally abundant for all EZ positions below 92 km.

These results agree with those obtained by Arthur and Ball (1980) and Cloern et al. (1983) and reiterated in Section 3.4 for chlorophyll. The cause is not clear. Although there is reason to believe that phytoplankton grow better in shallow than deep waters owing to differences in light for photosynthesis, estuarine zooplankton in general avoid the surface and therefore are usually less abundant in shallow than in deep water. A comparison of abundance anomalies of *Eurytemora* at the two shallow stations in Suisun and Honker Bays with values from nearby deep stations shows no significant difference (Figure 44). Therefore a higher growth rate in the shallows is unlikely, and another mechanism for concentration must be sought.

3.5.4 Effects of Export Pumping

The potential for effects of export pumping on zooplankton abundance is addressed in this section. Other possible causes of the relationship between EZ position and zooplankton abundance are discussed in Sections 3.5.5 and 4.2.

A possible cause of reduced abundance when the EZ is upstream is direct removal by the water projects. I have examined this question in two ways. First, if removal by the projects is important, abundance of *Eurytemora* should be higher in the San Joaquin than the Sacramento River. Figure 46 shows the difference in abundance anomaly between stations in the two rivers matched for distance up the estuary, separately for each of the four ranges of EZ position. Using the anomalies eliminates effects attributable to salinity, and using matched stations eliminates effects of distance upstream. Anomalies were always significantly higher (ANOVA, $p < 0.01$) in the Sacramento River when the EZ was upstream

3-11

of the confluence (Figure 46). This may suggest that reverse net flows in the lower San Joaquin River, which generally occur when the EZ is upstream, draw zooplankton upstream. Anomalies were higher in the San Joaquin at the upstream stations when the EZ was downstream of the confluence (Figure 46), probably because flows are higher in the Sacramento River than the San Joaquin when the EZ is downstream (based on examination of DAYFLOW values).

To determine the effect of export pumping on populations of EZ zooplankton, I used two approaches. The first is based on the relationship between salinity and abundance of the two species, and on the salinity of exported water. This does not generally exceed 0.25, at which abundances of both *Eurytemora* and *Neomysis* are less than 10% of their mean abundances within the EZ (Figures 32 and 34). The export rate is about 0.01 km^3/d in summer, based on DAYFLOW values. When the EZ is upstream its volume is about 1 km^3 (Figure 16). Assuming that the population size is approximately equal to the volume of the EZ multiplied by the long-term mean abundance from Figures 32 and 34, and that the abundance-salinity relationships upstream of the EZ represent a mixing process, the proportion of the population exported will not exceed about 0.1%/d, since the volume exported is 1% of the EZ volume and the maximum abundance exported is not over 10% of the EZ abundance.

For an alternative analysis, I used data from two stations in the southern Delta, one in Old River and one in Middle River. For each month, I calculated the abundance of *Eurytemora* in each of these locations. I used the DAYFLOW values for mean monthly exports to obtain the pumping rate. I assumed as a worst case that all of the water going to the pumps came upstream through the Old and Middle Rivers, and that none of it came from the San Joaquin. This allowed me to avoid any questionable assumptions about flow splits within the Delta, resulting in a very conservative figure for the rate of removal of *Eurytemora* from the population. Next I calculated the mean abundance for each km of distance along the estuary and converted this to absolute abundance (total numbers per km) by multiplying by the estimated cross-sectional area. I then summed these values to obtain the size of the population for each month. Finally, I divided the population size into the estimated rate of removal by the pumps to arrive at the proportion of the adult population removed per day. I assumed that juveniles of the same population would be removed at the same rate.

The median percent exported was 0.06%/day (Figure 45). Three values over 10% appear to have been spurious, based on examination of the raw data. About 13% of the values were over 1%/d, and many of these values were in late 1987 to 1988 when abundances were greatly reduced in the entrapment zone. Typical reproductive and growth rates of copepods of this size at spring to summer temperatures are 10-20%/d (Burkill and Kendall 1982, Kimmerer and McKinnon 1987). This result, confirms that from the cruder calculation described above to show that export pumping has rarely (if ever) had a direct effect on the copepod population.

3.5.5 Correlations of Zooplankton With Measures of Food Concentration

An additional possible explanation for the higher abundance of zooplankton when the EZ is downstream is that food (as measured by chlorophyll) is higher (Orsi and Mecum 1986). Although it is true that the two variables are correlated, the relationship appears to be a result of similar (mainly physical) causes of the spatial and temporal patterns. If anomaly values with salinity and seasonal patterns and annual trends removed are used for both variables, the regression is still significant (p<0.001), but explains only 0.3% of the variance in the *Eurytemora* anomaly, and 0.1% of the variance in the original data. If monthly means are used, even this minor effect disappears. Thus the relationship between *Eurytemora* abundance and chlorophyll seems to be a result of similar relationships of these variables to other factors such as salinity, season, and long-term trends.

A correlation between inverse Secchi depth and *Eurytemora* abundance is more robust, with $r^2 = 0.035$; that is, turbidity explains about 3.5% of the variance in *Eurytemora* anomaly (p<0.001). This may suggest that some of the variation in *Eurytemora* abundance is an artifact of the influence of light levels on vertical distribution, or it could simply mean that both variables respond similarly to changes in physical conditions. This correlation is unlikely to have arisen from a sampling artifact, since the samples are taken by oblique tows from the bottom to the surface, and the vertical distribution of *Eurytemora* is broad (J. Orsi, DFG, pers. comm.).

3.6 STRIPED BASS

Considerable analysis has gone into the data on striped bass, and relatively little new analysis has been done for this report. A great deal more could be done, particularly with the data on spatial and temporal distribution of bass larvae. These data consist of abundances of eggs and of larvae in 1-mm size intervals from samples taken every 4 days at a large number of stations. A thorough analysis of these data to determine spatial and temporal patterns of growth and mortality would require considerable effort including a calibrated hydrodynamic model, which is not yet available.

Most of the analysis presented here uses the annually aggregated abundance indices, which consist of time- and volume-weighted total numbers of striped bass eggs and of larvae in each size class. Several assumptions are implicit in this use of the data: 1) That growth and mortality of a given size class are nearly constant within any one year; 2) That exchange among various parts of the habitat is sufficient to insure that a single population exists, i.e. that there are not subpopulations isolated from each other; and 3) That sampling is frequent enough to obtain a reliable average of abundance at all stages. This is clearly not the case for eggs, which occur in large peaks of only a few days' duration (USBR 1990). However, the sampling interval may be sufficiently short to sample adequately the larvae, since they take several days to grow 1mm (DFG 1988b).

As pointed out in Section 2.4.3, striped bass are not confined to the entrapment zone, but they are most abundant there. Figure 47 presents the median salinity class of striped bass

larvae by size class for 1986. The earliest larvae, 3-5 mm in length, were in relatively fresh water, but as the larvae developed they occupied a generally increasing salinity regime so that the largest larvae were most abundant at the upstream edge of the entrapment zone. Given that the actual entrapment zone is somewhat upstream of the operationally defined location when flow is high (as it was in 1986), this indicates that these fish are strongly concentrated in the EZ. This is consistent with the behavior of larvae loss (Section 2.4.3).

The contention of DFG is that the egg supply has declined, resulting in lower young-of-the-year indices (YOY). By any of the three indices, egg abundance has indeed declined over the period from 1969 to about 1980, and has then leveled off (Figure 48). Although the discrepancy among the egg abundance indices is as much as a factor of 5, all indices show a decline in egg abundance. Relative survival from egg to YOY, calculated as the log of the ratio of YOY to the egg indices, has apparently not declined over this time period by any measure of egg abundance (Figure 49); in fact, the highest values of relative survival occurred in the 1980s. Interannual variability in this survival index is large, however, with up to a 10-fold variation in YOY for a given number of eggs. This interannual variability is significantly related to position of the EZ (Figure 50; $p < 0.001$, $R^2 = 0.33$, linear regression), although flow explains somewhat more variance ($R^2 = 0.43$).

4.0 DISCUSSION

The following section attempts to answer each of the questions posed in the Introduction to the extent possible, and to evaluate the ability of the previous literature and this analysis to answer them. The next section discusses a number of hypotheses for the enhancement of zooplankton abundance at intermediate or downstream positions of the EZ. Next, recommendations are provided for future data gathering and analysis, and a series of conclusions is presented.

4.1 QUESTIONS ON THE ENTRAPMENT ZONE

This section presents points relevant to answering each of the questions posed in the Introduction. It also discusses the utility of the monitoring data in providing answers not available in existing reports. To minimize repetitive citations, each point made is accompanied by the numbers of the previous sections in which they have been discussed.

4.1.1 Characteristics of the Entrapment Zone in the San Francisco Bay Estuary

In general, the physical, chemical, and biological characteristics of the EZ have been well known for over a decade. Analysis of the monitoring data has provided only a few additional insights. This does not reflect a deficiency in the data (or, I hope, the analysis), but rather reflects the fact that considerable effort has gone into special studies designed to address specific questions regarding the entrapment zone.

The following key points have emerged regarding the entrapment zone of the San Francisco Bay estuary (Numbers in parentheses are sections where these are discussed):

- The EZ is a persistent feature of the estuary.

- The operational definition of the EZ used by Arthur and Ball (1979), i.e. a salinity range of 1-6, should be regarded as a useful surrogate for actual data on velocity profiles for determining the approximate location of the EZ (3.2.2).

- The operationally defined EZ moves up and downstream in response to flow, but with considerable variation due to effects of wind and tide (2.2, 2.3, 3.2.2).

- As the operationally defined position of the EZ varies from 65 to 95 km from the Golden Gate Bridge, the difference between the actual position and the operationally defined position varies by about 8 km. This is because the operational definition uses surface conductivity, ignoring the increase in stratification occurring with a more downstream position of the EZ (3.2.2).

- The concentration of particles, chlorophyll, some phytoplankton and zooplankton species, and larval stages of Delta smelt and striped bass are enhanced in the EZ (2.3, 2.4, 3.4, 3.5, 3.6).

- Nutrient concentrations are not remarkably different in the EZ than elsewhere (3.3).

4.1.2 Importance of the EZ to Biological Production

Biological production has two components, biomass and growth, either or both of which could vary within the estuary. Although growth is rarely measured, primary production and phytoplankton biomass have been measured fairly often. Again, the importance of the EZ to biomass or abundances of most species has been fairly clear for some time. Key points arising from this analysis are:

- Phytoplankton specific growth rate is probably depressed in the EZ relative to other areas of similar depth because of reduced light penetration (2.3, 2.4, 3.2.2).

- Phytoplankton biomass is enhanced, probably by simple entrapment of species with sinking rates in a certain range (2.4, 3.4).

- There is no evidence that growth rates of zooplankton are higher in the EZ than out of the EZ (2.4.2).

- Based on the (limited) evidence to date, it is likely that the elevated abundance of zooplankton and fish are a result of entrapment rather than a response to higher food levels (2.4.2, 2.4.3, 2.5).

- Similarly, production of zooplankton and fish is probably more closely related to biomass than to growth rate, which may be less spatially variable than biomass. Therefore production of entrapment zone species of zooplankton and fish is also higher in the EZ than outside (2.4.2, 2.4.3).

4.1.3 Importance of EZ Position to Abundance or Production

The relationship of phytoplankton to EZ position was well described, and its probable cause explored, by Arthur and Ball (1980) and Cloern et al. (1983). These results were based on sampling and experimental studies designed specifically to elucidate the cause of the observed variation in phytoplankton biomass with EZ position. Therefore examining the monitoring data has added little to that area. The analyses of striped bass and Delta smelt have also received a great deal of attention, and little has been gained by further analyses of the striped bass data (but see Section 36). Because the zooplankton have received less scrutiny and have not been the subject of many special studies, there was a somewhat greater opportunity to learn more of the effect of EZ position on these species than on others. To summarize, the following statements can be made regarding the effect of EZ position:

- The volume of habitat, defined as a range of salinity values, is highest when the EZ is downstream and lowest when it is upstream (Figure 16).

- If abundances did not change with EZ position, total population sizes would be greater when the EZ is downstream (based on above).

- Phytoplankton production is enhanced when the EZ is downstream, most likely by the mechanism proposed by Cloern et al. (1983) (2.4.1).

- Abundance of Eurytemora is marginally higher when the EZ is below 72 kg in spring, and significantly higher when the EZ is between 72 and 92 km in fall, compared to other positions (3.5.3).

- Abundance of Neomysis is significantly higher when the EZ is below 82 km than when it is upstream, for the entire dataset through 1987 (3.5.3).

- These differences in abundance imply a difference in production, since there is no reason to expect higher growth rates when the EZ is upstream (2.4.2, 3.5.3).

- Striped bass move down into the EZ during larval development. Survival from egg to YOY is positively correlated with position of the EZ, but since correlations of survival with flow are higher, the relationship with EZ may actually indicate a relationship with flow (2.4.3, 3.6).

- Delta smelt indices are also positively related with EZ position, but it is not clear whether this is a direct relationship or the result of covariance with flow (2.4.4).

4.1.4 Relationship of Historical Declines to Changes in the EZ

The position of the EZ is related to flows, which have changed substantially over the last decades both in quantity and timing (Nichols et al. 1986). However, more recent changes in the estuary do not appear to be related to EZ position, as discussed below:

- During 1972-88, when the data analyzed here were collected, export flows increased by about 3000 cfs (3.2.1).

- During the same period, no consistent trend in EZ position is apparent, mainly because wide interannual variations in Delta inflow masked the trend due to the increase in exports (3.2.1).

- Most of the measures of biological abundance and (implied) production declined significantly over the period 1972-88. These included chlorophyll, abundances of *Eurytemora* and *Neomysis*, striped bass YOY index, and Delta smelt abundance (2.3, 2.4, 3.4, 3.5, 3.6).

- Survival of striped bass from egg to YOY did not change over this period (3.6).

- Most of the measures of biological abundance and production were related to EZ position, with highest values when the EZ was below the confluence of the Sacramento and San Joaquin Rivers (3.4, 3.5, 3.6).

- The declines in abundance of these measures cannot be attributed to long-term changes in EZ position because there was no trend in EZ position; in addition, the magnitude of the differences in abundance among different EZ positions was much less than the magnitudes of the declines for many of these measures (3.2, 3.4, 3.5, 3.6).

- EZ position appears important in its relationship with relatively short-term, interannual variation in biological indicators; that is, the long-term trends in abundance are superimposed on fluctuations in abundance due partly to changes in EZ position (from above statements).

- For *Eurytemora* and *Neomysis*, the variation of abundance with EZ position is not due to changes in exposure of the population to export pumping (3.5.3).

- During the entire period 1972-1990, the most striking and apparently permanent changes in the EZ have resulted from inadvertent introductions of new species. These are unrelated to characteristics of the EZ other than its suitability as habitat to new species, which would be difficult to predict (3.4, 3.5).

4.2 MECHANISMS FOR VARIATION OF ZOOPLANKTON AND LARVAL FISH WITH EZ POSITION

A number of possible causes of the relationship between zooplankton abundance and EZ position can be imagined. In this section I attempt to list them and to describe evidence for or against each one. Larval fish are discussed below. Only one of these relates directly to the position of the zone; the remainder ascribe the relationship to a correlate of EZ position. When the EZ is downstream, flow is high, phytoplankton abundance is often high, and stratification and presumably two-layer flow are strong. The postulated mechanisms include:

1) A similar model to that proposed by Arthur and Ball (1980) and Cloern et al. (1983) holds for zooplankton: that is, growth is faster in shallow than deep water and therefore the population is larger when the EZ is adjacent to shallow water.

For: None
Against: *Eurytemora* abundance was not greater at a shallow station in Suisun Bay compared to a nearby channel station (Figure 4.4).

2)   Zooplankton removal by export pumping is enhanced when the EZ is upstream and the zooplankton are more vulnerable to pumping.

        For: Clear relationships exist between outflow and EZ position, and between outflow and percent exported. In addition, the centers of populations of EZ species are closer to the pumps and therefore more vulnerable when the EZ is upstream.

        Against: Even with the EZ upstream the amount exported was calculated to be trivial. However, the actual export rate has not been determined.

3)   Higher phytoplankton biomass and productivity when the EZ is downstream support more rapid zooplankton growth and therefore higher abundance.

        For: Abundances of EZ species are highest near the peak in chlorophyll. In addition, the abundances of zooplankton have been remarkably stable over the last decade (until 1988), suggesting a regulatory mechanism such as food supply.

        Against: Correlations between zooplankton and chlorophyll appear to be artifacts of covariation of each to other variables. Also, there is some experimental evidence that *Eurytemora* reproduction is not food limited.

4)   Higher input of organic matter to the EZ results in higher biomass of bacteria and microzooplankton that provide alternative food sources to the zooplankton.

        For: The concentrations of nutritive material and bacteria are higher in the EZ than outside. Whether these change with EZ position is unknown.

        Against: See #4.

5)   The observed difference is an artifact caused by the sampling method.

        For: None

        Against: Abundances at shallow and deep stations were similar.

6)   Behavioral mechanisms for remaining in the entrapment zone are enhanced by the greater strength of two-layer flow.

        For: There is ample evidence that tidally-mediated position maintenance is common in estuarine zooplankton, and some evidence that it happens in this estuary. There is no information with which to evaluate the effect of variation in the strength of entrapment.

        Against: None

7)   Complex circulation in Suisun and Honker Bays, caused by interactions of flow and topography, provide a horizontally oriented entrapment mechanism that enhances the more usual vertically oriented mechanism.

     For: None
     Against: None

At this point it would be virtually impossible to rule any of these out, but the first four are unlikely to be correct. The similar abundances in shallow and deep water are evidence that shallow water is not an unusually productive location. Furthermore, there is no *a priori* reason to expect higher growth in the shallows, since zooplankton are not generally dependent on light levels for feeding. The analysis reported above on abundance of *Eurytemora* in Old and Middle Rivers suggests that export pumping is not a major source of losses to the population. Furthermore, the lack of food limitation of *Eurytemora* in the 1988 experiments is a hint that zooplankton growth and abundance do not respond strongly to increased abundance of phytoplankton or detritus.

There is a possibility that an artifact of sampling produced the results shown. *Eurytemora* and *Neomysis* both remain near the bottom by day. The sampling method used, oblique tows from near the bottom to the surface, may miss some organisms very close to the bottom. If the vertical distribution changes with light level, for example, then a strongly developed, turbid EZ would result in a higher catch since the animals would be further off the bottom. However, the finding that abundances in deep and shallow stations did not differ suggests that this is not a major problem.

The remaining mechanisms bear further investigation, since they appear to be the most consistent with the available information. Mechanism 6 implies that either the zooplankton detect and respond to changes in flow, or that their behavioral pattern is designed to maximize entrapment under intermediate to high flows. This seems likely on the basis of the extensive behavioral repertoire of zooplankton, but cannot be resolved with the monitoring data.

Mechanism 7 is also likely to operate. Zooplankton populations are often enhanced near topographic irregularities that result in eddies and other flow complexities (Trinast 1975, Alldredge and Hamner 1980). The circulation of Suisun and Honker bays is complex, and there is reason to believe that eddies can occur there. As with mechanism 6, there is no way to resolve this with the data at hand.

Larval striped bass also appear to survive better when the EZ is downstream of the Delta (Section 3.6), and Delta smelt may have higher year classes when the EZ is downstream (Section 2.4.4). The mechanisms for these relationships probably include those listed above, but some of the arguments presented do not hold for larval fish. For example, shallow regions of the estuary provide habitat for some planktivorous fish including Delta smelt (Moyle et al. in prep.), so maintenance of the EZ in Suisun Bay would provide more habitat for this species. In addition, the interannual variability in growth rates of larval striped bass

probably indicates food limitation, so bass growth (and probably survival) would be enhanced when the EZ is downstream. Of the above mechanisms, #1-3, 6, and 7 all appear reasonable and somewhat supported by evidence (substituting zooplankton for phytoplankton and fish for zooplankton).

4.3 RECOMMENDATIONS

Although the State Water Contractors are not directly involved in the monitoring programs, they may find it useful to consider the following recommendations in discussing the goals and operation of the sampling program with Interagency personnel. These recommendations are aimed primarily at improving the utility of the raw data gathered by these programs. That is, the raw data need to be converted into knowledge.

- Effort should be allocated in equal proportions between gathering data and analysis, with procedures established to insure timely analysis, reevaluation of usefulness of the data, and incorporation of the new knowledge into an accumulating conceptual model.

- Effort should also be reallocated from monitoring to special studies, either sampling and analysis for particular purposes or experimental work.

- The data storage system should be scrapped and replaced with a modern relational database.

- Some effort should be expended to determine the importance and role of microbial and microzooplankton activity in processing nutrients and organic matter in the entrapment zone.

An additional series of recommendations relates to the need for a large-scale field study of the entrapment zone. Such a study was discussed by several Interagency groups in 1989, but may not be warranted until one or two wet years have passed and we can see what happens with the introduced clam. If and when such a study were to be undertaken, it should be designed carefully to answer the following questions:

- How well does the position of entrapment as determined by tidally-averaged velocity profiles agree with the operationally defined location of the EZ?

- What is the relationship between surface salinity and salinity profiles at various EZ positions and outflows?

- What is the relationship between the strength of entrapment, as determined by peaks in concentration of various substances, and the position of the EZ?

- How do zooplankton and striped bass larvae move longitudinally in the estuary as a result of their vertical positions?

None of these questions is trivial. If the study is planned for several years from now, it might benefit from close ties to a major study funded by the National Science Foundation to examine similar questions in the Columbia River estuary. To the extent that the two estuaries are similar, it would be very beneficial to maintain close ties with that project. Several of the members of the Food Chain Group, myself included, are doing that now.

4.4 CONCLUSIONS

During the period of record from about 1972 to the present, no trend in EZ position is evident, either for the data as a whole and for individual seasons. This is because the EZ is most affected by outflow, which has had no consistent trend during this period and in which, variation within and between years is large enough to swamp the variation due to increasing exports. This is not to say that exports have had no effect, merely that during this time period the increase in export flows formed a minor part of the variation in outflow. In fact, exports have averaged about 34% of exports plus outflow for the entire period, a substantial fraction. An increase of outflow of this magnitude would move the EZ downstream on average by about 5 km. In the summer exports are about equal to outflow, and elimination of exports (and maintenance of inflows) would move the EZ downstream by about 8 km.

The key conclusions of this effort are as follows:

- The entrapment zone is as important to the estuary as has been maintained by previous reports, in that it is the most productive area for phytoplankton and zooplankton.

- The location of the entrapment zone is correlated with abundance of many of the biota of the estuary, but the mechanism for this is unknown; in fact, the correlation may be due to underlying relationships with flow, strength of entrapment, or other variables rather than a direct effect of EZ position.

- The importance of the entrapment zone to striped bass is not fully demonstrated, although the growing evidence that larvae are food limited suggests that variation in zooplankton could be important to bass, and therefore that bass survival should be higher in the EZ.

- Although export pumping has increased during 1972-88, the larger interannual variation in Delta inflow has masked any effect on EZ position during this period. However, flows in Delta channels may have changed during this period.

- For maximum production of zooplankton the entrapment zone should be at least as far downstream as the confluence of the two rivers.

- Declines in biological variables over the period 1972-1987 are significant but apparently not related to changes in flow or position of the entrapment zone.

- Recent changes in the estuary, particularly the introduction of *Potamocorbula amurensis*, may make the above moot, at least as far as *Eurytemora* is concerned.

- The existing monitoring programs have provided a good database for detecting trends but have not included sufficient analytical effort to detect the changes in a timely manner, nor have they incorporated the flexibility needed to respond to changes detected.

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6.0 GLOSSARY

Abundance   The number of organisms per unit volume or area, usually expressed as numbers per cubic meter or square meter or multiples of those units. Equivalent to Concentration or sometimes Density.

Abundance index   A number assumed proportional to the total number of organisms in a population (e.g. juvenile striped bass). This use is misleading, since it refers to Population size (total numbers) instead of Abundance (defined above).

Analysis of Variance (ANOVA)   A form of statistical analysis in which the total variance in the data is partitioned into the variance from different sources, which is then compared with the remaining (error) variance.

Anomaly   The difference between a data value and the mean for some grouping or class (e.g. year, month, salinity class).

Biomass   The amount of weight or mass of living material in a given category per unit volume or area, usually expressed as dry weight, carbon, energy, or for phytoplankton, chlorophyll.

Chlorophyll   A photosynthetic pigment found in all green plants. Chlorophyll a is used as a measure of phytoplankton biomass.

Confidence limit   A measure of the degree of certainty with which we can state a given statistic. If we have a sample mean with 95% confidence limits, there is a 5% chance that the actual population mean falls outside those limits.

Copepod   A class of small crustaceans that make up the bulk of the zooplankton in the ocean and most estuaries; these may be the first or second most abundant animals on Earth.

Correlation   A measure of the degree of association between two variables: a value of 1 means that they have an exact, linear relationship, -1 means that they are exactly but inversely related, and 0 means that they are completely unrelated.

Detritus   Non-living particulate organic matter, usually derived from living organic matter.

Entrapment zone (EZ)   The area of the estuary where flow convergence results in the concentration of particulate matter; this usually operates through the interaction of particle (or organism) sinking and net up-estuary flow at depth (See Operational Definition below).

Estuarine turbidity maximum (ETM)   An area of the estuary where turbidity is enhanced, either by entrapment or other mechanisms.

Gravitational circulation Two-layer flow in an estuary, in which the slope of the surface of the water from the river to the ocean drives a seaward flow, while denser, saline water is driven inward by the effect of the density gradient. These flows are often detectable only as net (i.e. tidally-averaged) flows, if the tidal flows are much larger than the freshwater flow.

Log transformation The process of taking logarithms of data so that the data are suitable for parametric statistical testing (e.g, ANOVA, regression).

Null zone The location in the estuary at which net landward flow near the bottom ceases, and all tidally-averaged flow throughout the water column is seaward. This generally marks the upstream limit of the entrapment zone.

Operational definition of the EZ Since net flow velocities are difficult to measure except under high-flow conditions, an operational definition of EZ position is required to permit analysis of the effects of EZ position on characteristics of the estuary. The operational definition used here (after Arthur and Ball 1980) is the salinity range of 1.2-6 (specific conductance of 2-10 mS/cm).

Phytoplankton Planktonic algae, consisting of single cells or chains of cells.

Plankton Pelagic (i.e., living in the water rather than on the bottom). Plants or animals that are either small or have limited capabilities for motion.

Primary productivity The rate at which phytoplankton or other plants convert inorganic carbon to organic carbon, usually expressed as carbon per unit volume or area per hour.

Production The biomass of phytoplankton, zooplankton, or other group that is produced in a given time, usually expressed in terms of carbon per unit area or volume per day or year. It is equal to the product of biomass and growth rate averaged over the population and the chosen time period. Note that the term Productivity (above) is also often used in its more common meaning of capacity or ability to produce.

Regression A statistical technique for fitting a straight or curved line to a set of data.

Residual The difference between a data value and the value predicted by a regression line or other statistical model.

Salinity The concentration of salt in water. In ocean water salinity is determined from a fairly simple relationship with conductivity at 25°C. In the upper reaches of an estuary, some of the conductivity is not due to sea salt, so the relationship changes.

Secchi depth The depth to which a Secchi disk, a white or black and white disk, can be lowered and just remain visible; a measure of water transparency.

Specific growth rate The rate of growth of an organism divided by its weight, expressed as proportion (or percent) per day.

Specific conductance The electrical conductivity measured in a standard cell, corrected to 25°C, and expressed in millisiemens (mS) or microsiemens (μS) per centimeter of distance.

Spring/neap tides An oscillation in amplitude (high tide minus low tide height) of the tides on a 2-week cycle; the tidal amplitude can vary by over a factor of 2.

Turbulence Irregular motion of water caused mainly by shear between passes of water moving at different relative velocities. Responsible for most small-scale mixing.

Zooplankton Animal plankton.

Table 1. Salinity Classes Used in Data Analyses.

Salinity Class	Specific conductance (mS/cm) Range	Mean	Mean salinity
1	0.08 - 0.14	0.10	0.059
2	0.14 - 0.16	0.14	0.079
3	0.16 - 0.18	0.16	0.088
4	0.18 - 0.20	0.17	0.098
5	0.20 - 0.22	0.19	0.109
6	0.23 - 0.26	0.22	0.123
7	0.26 - 0.32	0.25	0.141
8	0.32 - 0.40	0.30	0.166
9	0.40 - 0.56	0.38	0.212
10	0.56 - 0.80	0.53	0.297
11	0.80 - 1.21	0.78	0.441
12	1.21 - 1.93	1.21	0.681
13	1.93 - 3.16	2.00	1.134
14	3.16 - 4.78	3.30	1.872
15	4.78 - 6.84	5.04	2.880
16	6.84 - 9.24	7.28	4.191
17	9.24 - 12.0	9.71	5.627
18	12.1 - 15.3	13.0	7.627
19	15.3 - 20.2	16.8	9.965
20	20.2 - 41.8	23.3	14.115
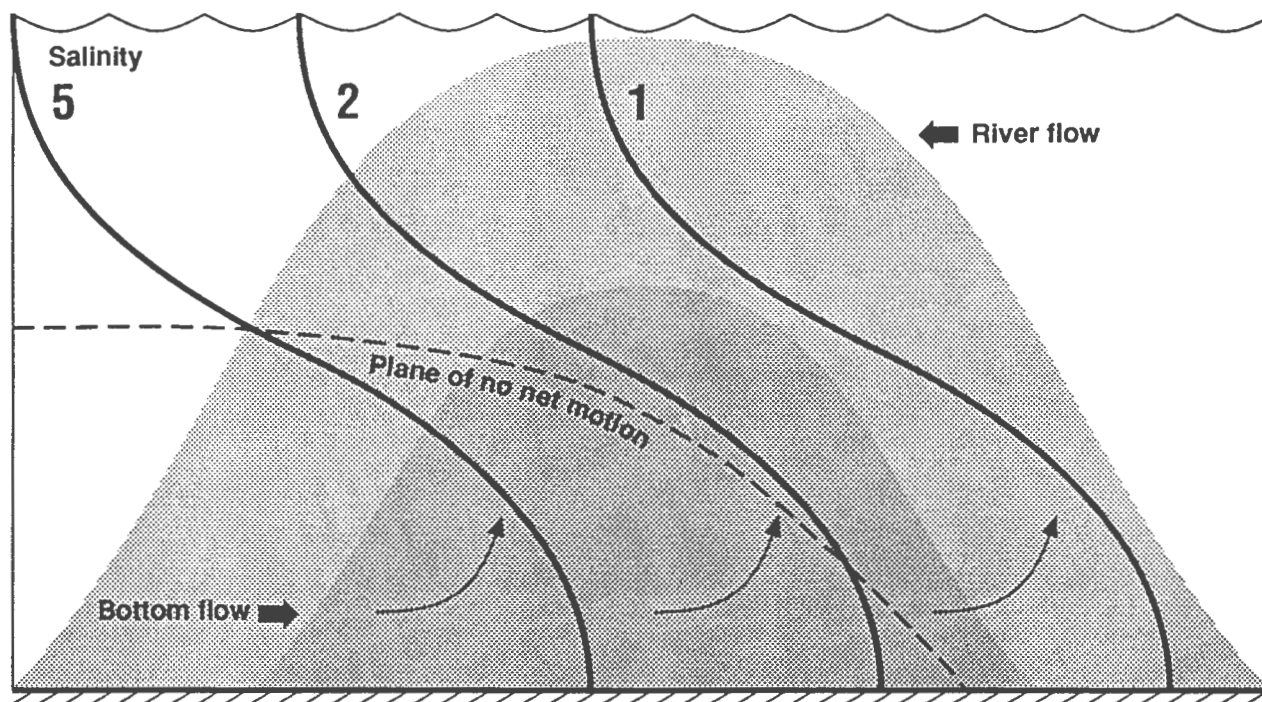
Figure 1. Schematic diagram illustrating the conceptual model of an entrapment zone. The shaded areas indicate the location of the turbidity maximum.
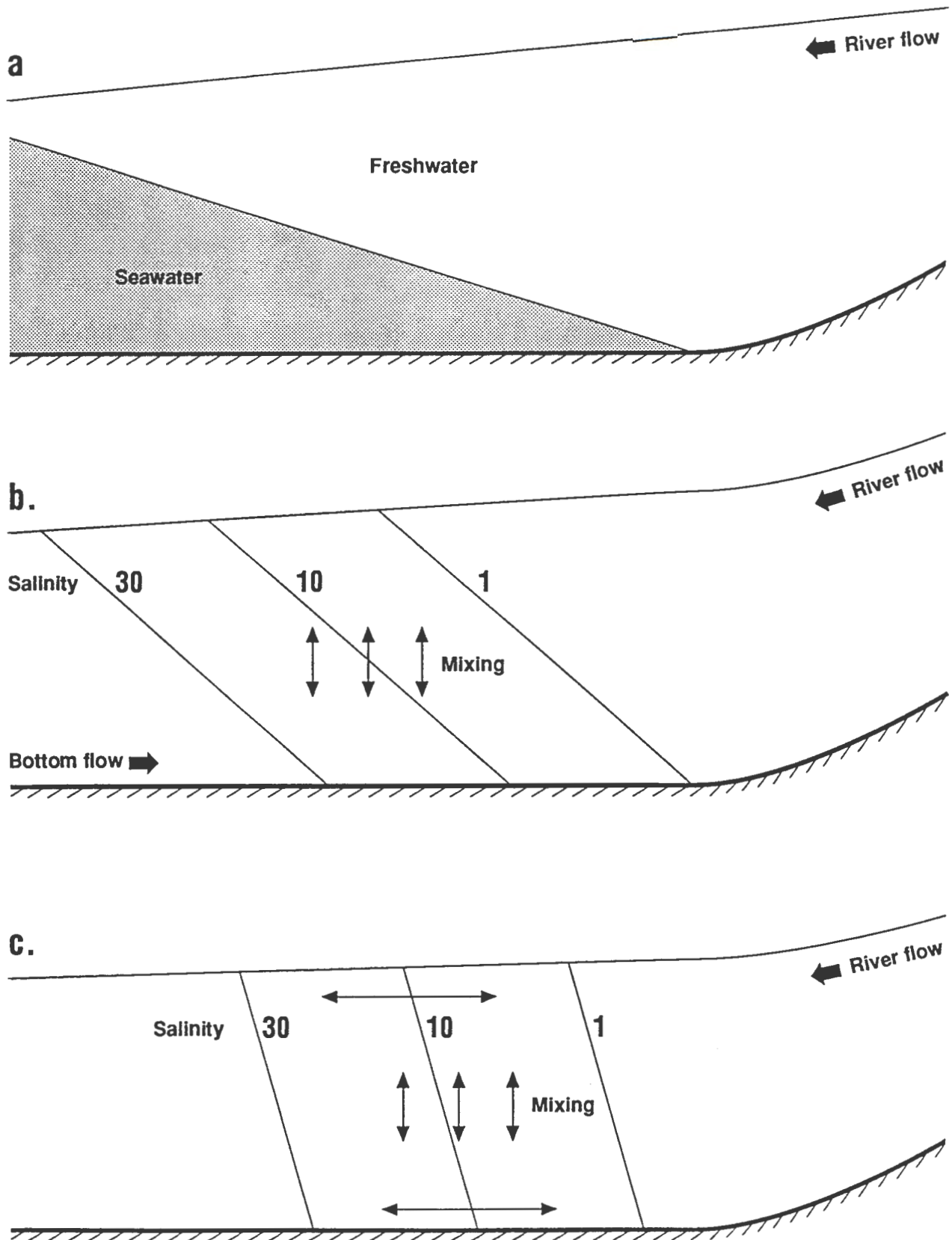
Figure 2. Schematic showing the effects of river flow, shear, and tides on salinity profiles in the estuary. **a.** No tides, no shear between layers. **b.** Shear but no tide. **c.** Both shear and tide.

Flood

Velocity
— 0 +
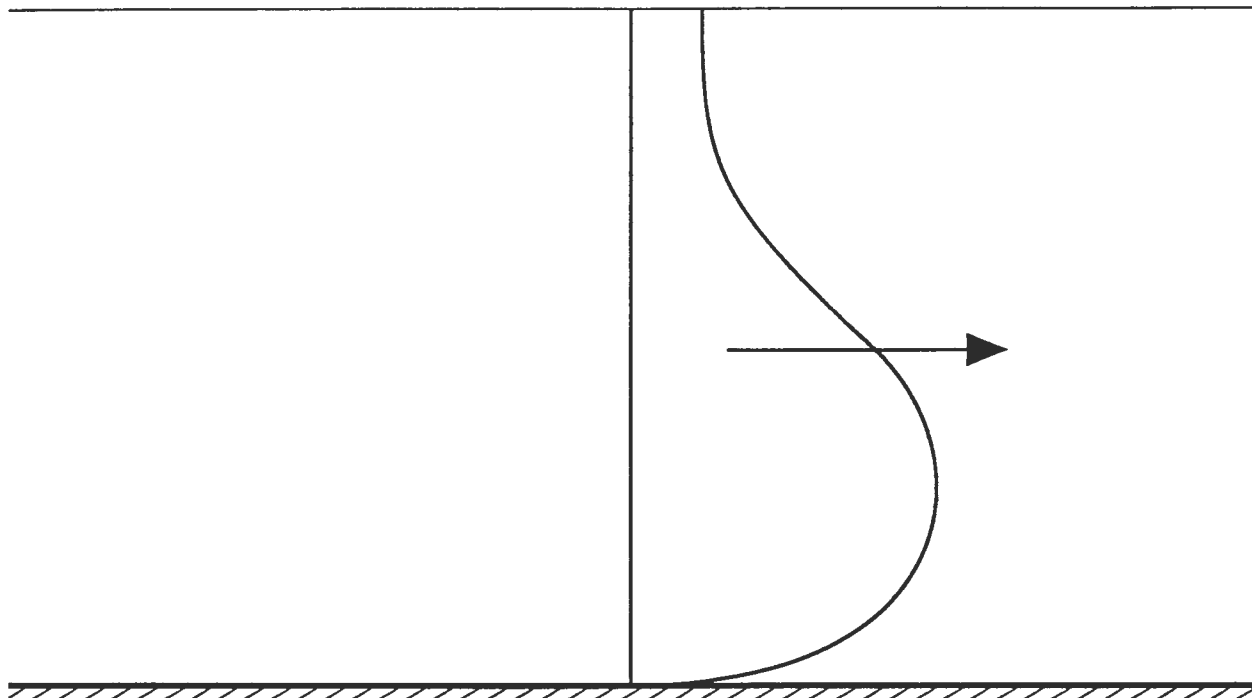
Ebb

Velocity
— 0 +
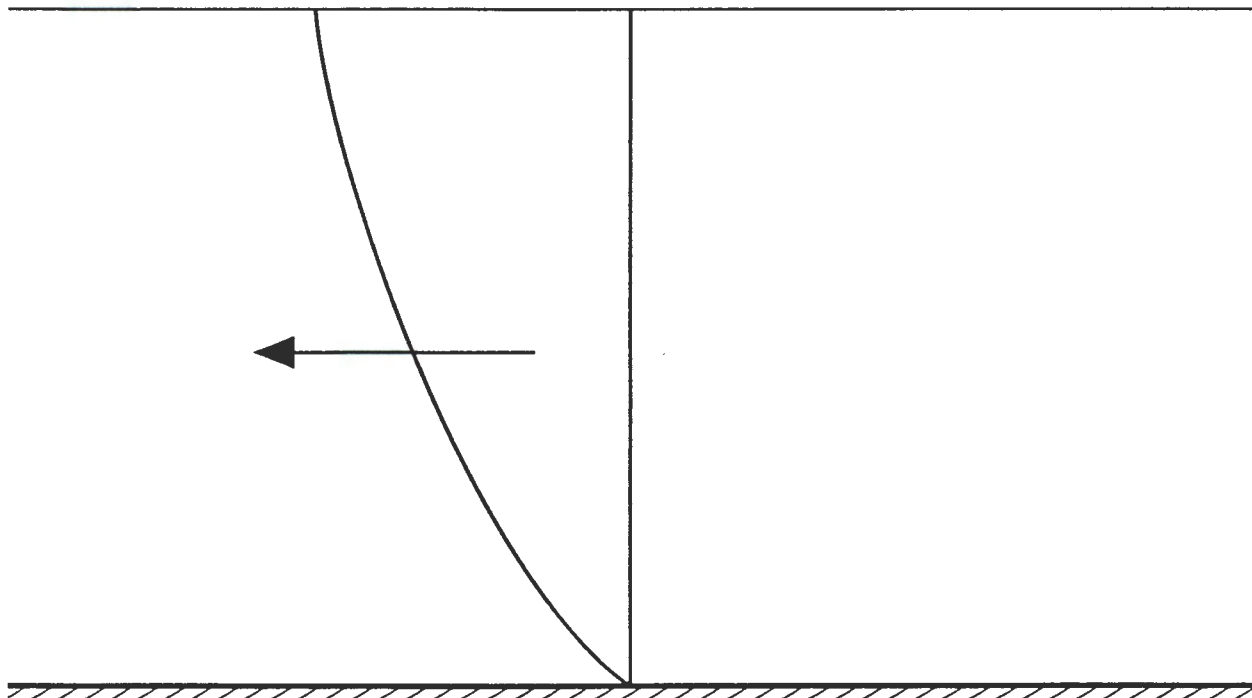
Figure 3. Schematic of ebb and flood velocity profiles.

Sacramento-San Joaquin River Delta

RIO VISTA

CHIPPS IS.

GRIZZLY BAY

SUISUN BAY

HONKER BAY

PITTSBURG

ANTIOCH

SACRAMENTO RIVER

SAN JOAQUIN RIVER

STOCKTON

TRACY

○ DFG Zooplankton Stations

● DWR Stations and DFG Zooplankton Stations
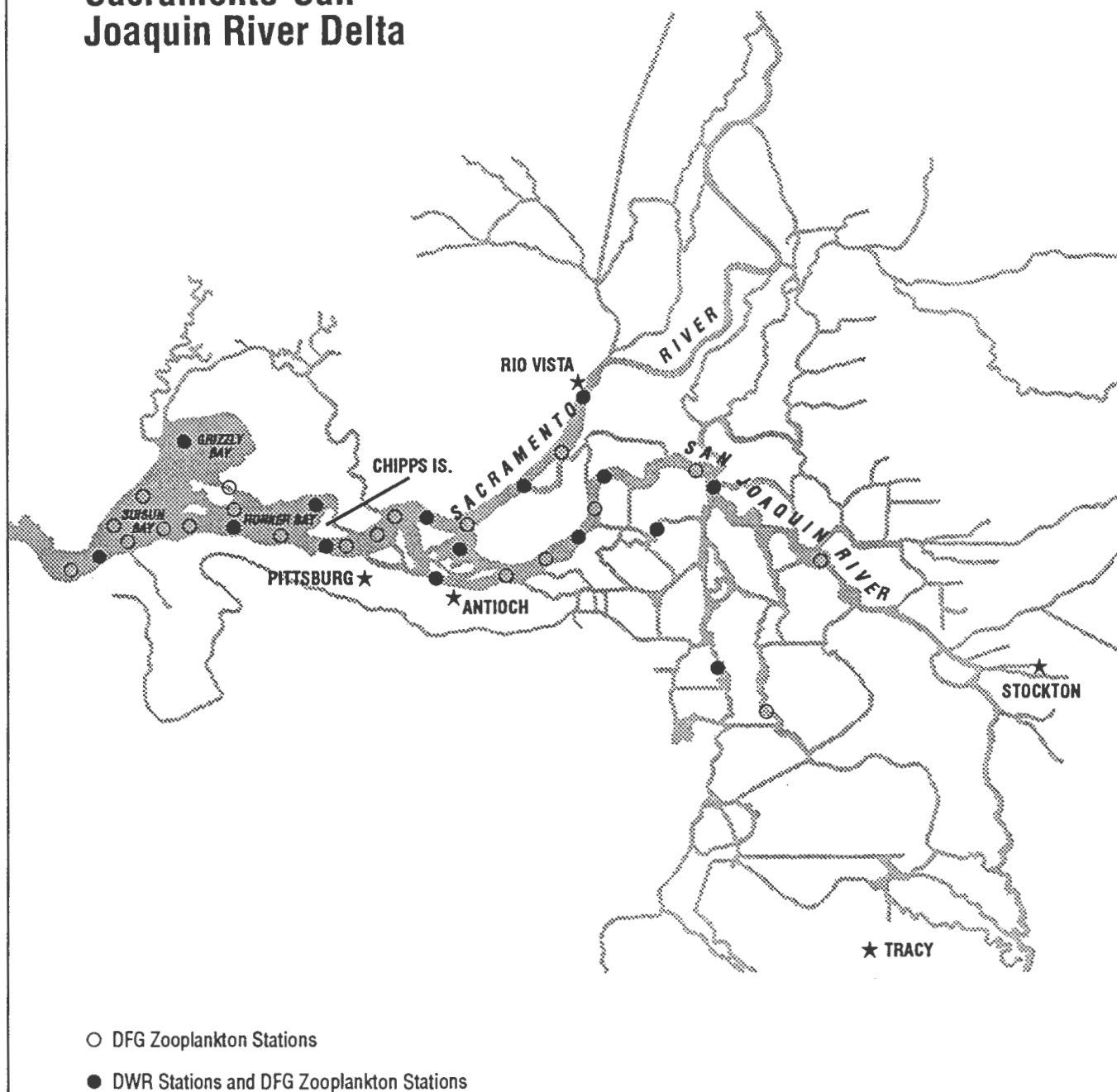
Figure 4. Location map for DWR and DFG sampling stations.
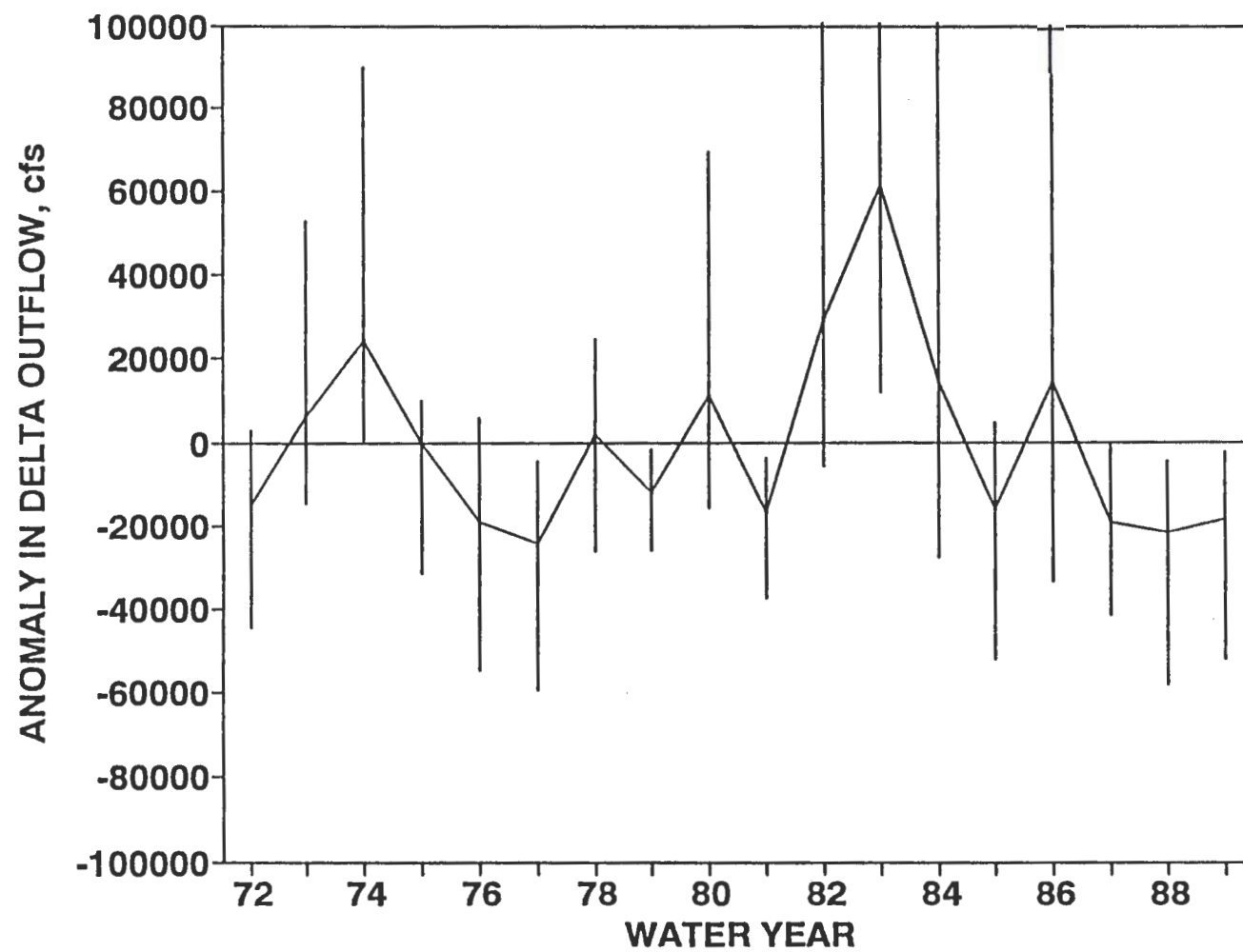
Figure 5. Anomaly in Delta outflow, annual means and 95% confidence limits.
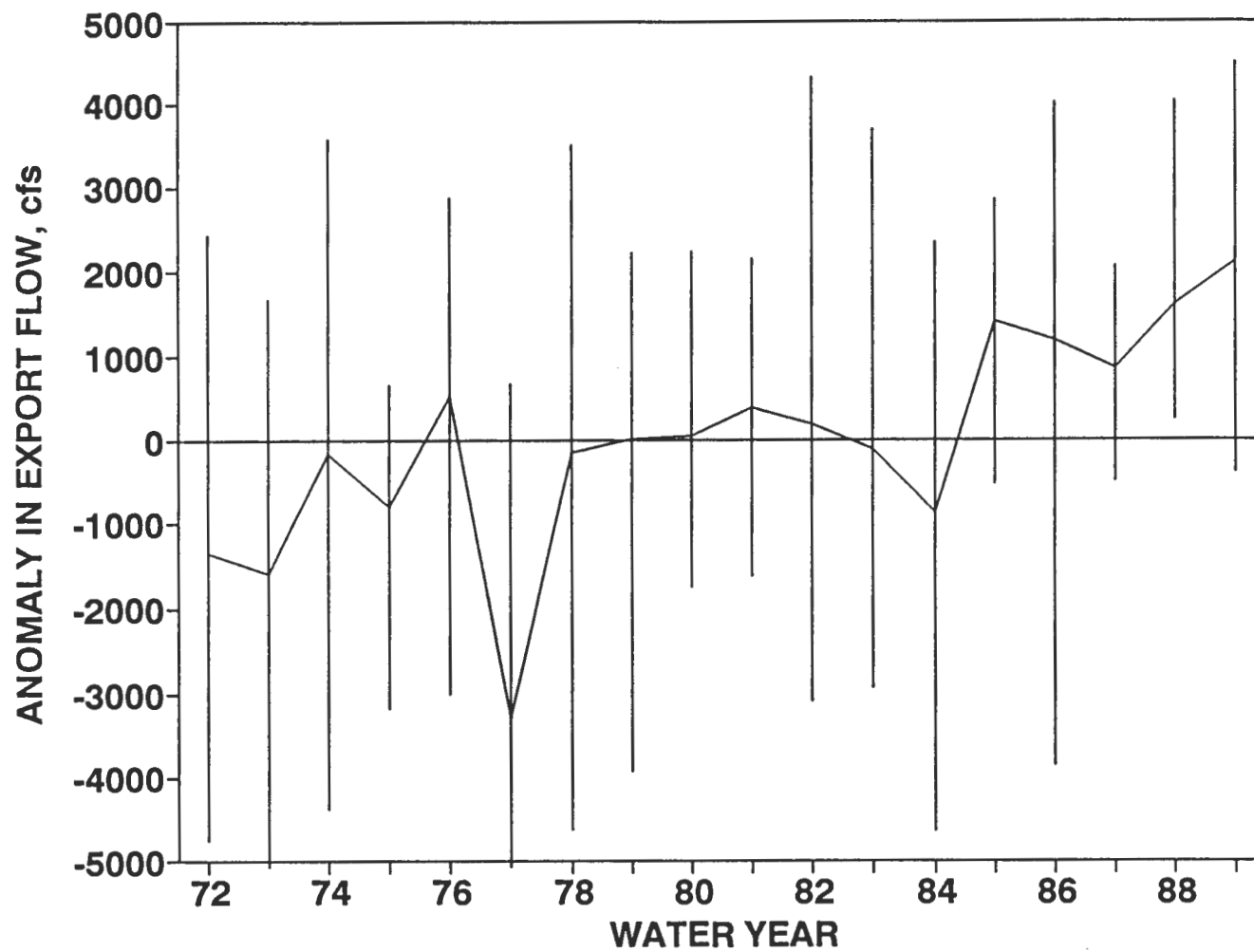
Figure 6. Anomaly in export flows, annual means and 95% confidence limits.
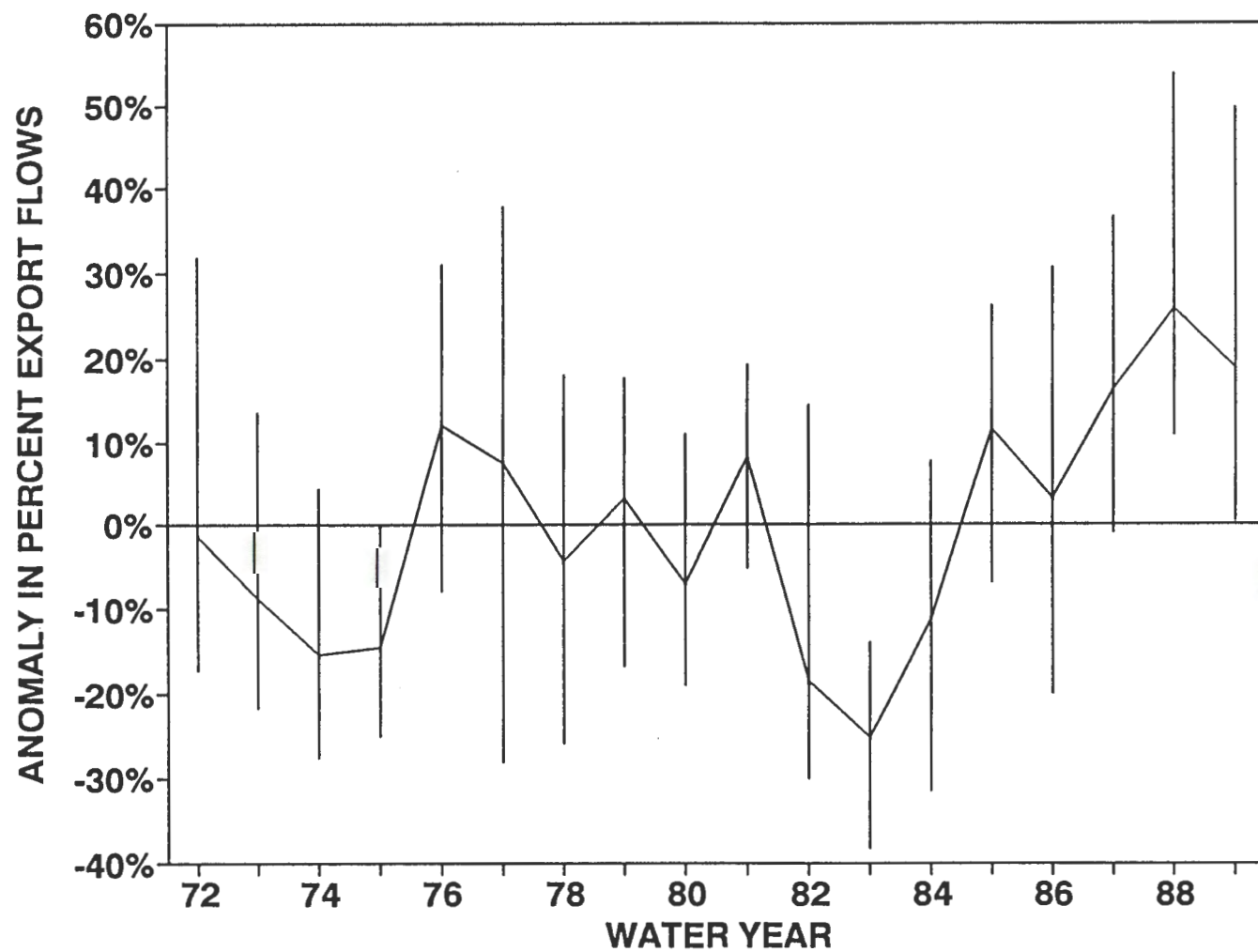
Figure 7. Anomaly in percent export flows, annual means and 95% confidence limits.
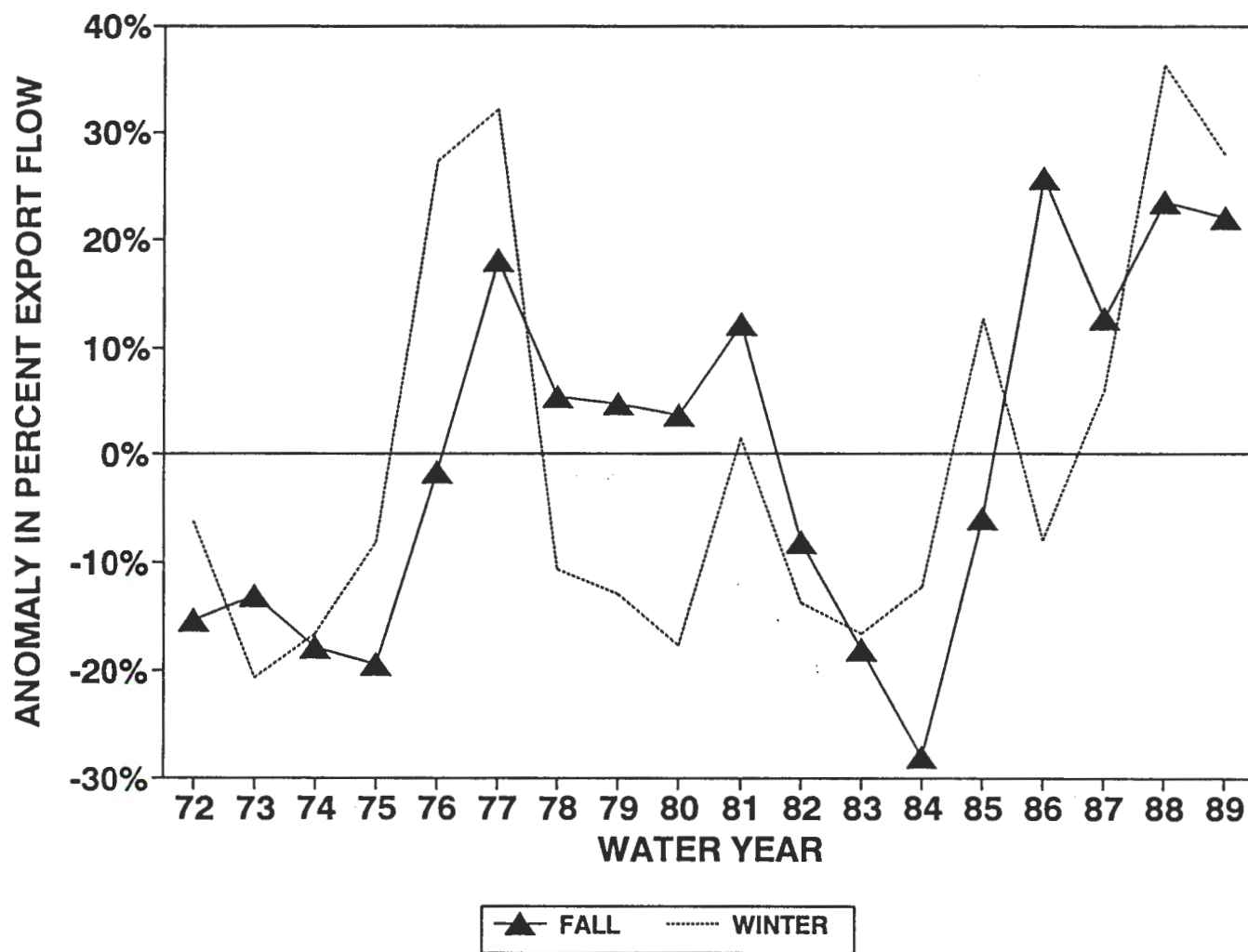
Figure 8. Anomaly in percent export flows for fall and winter.
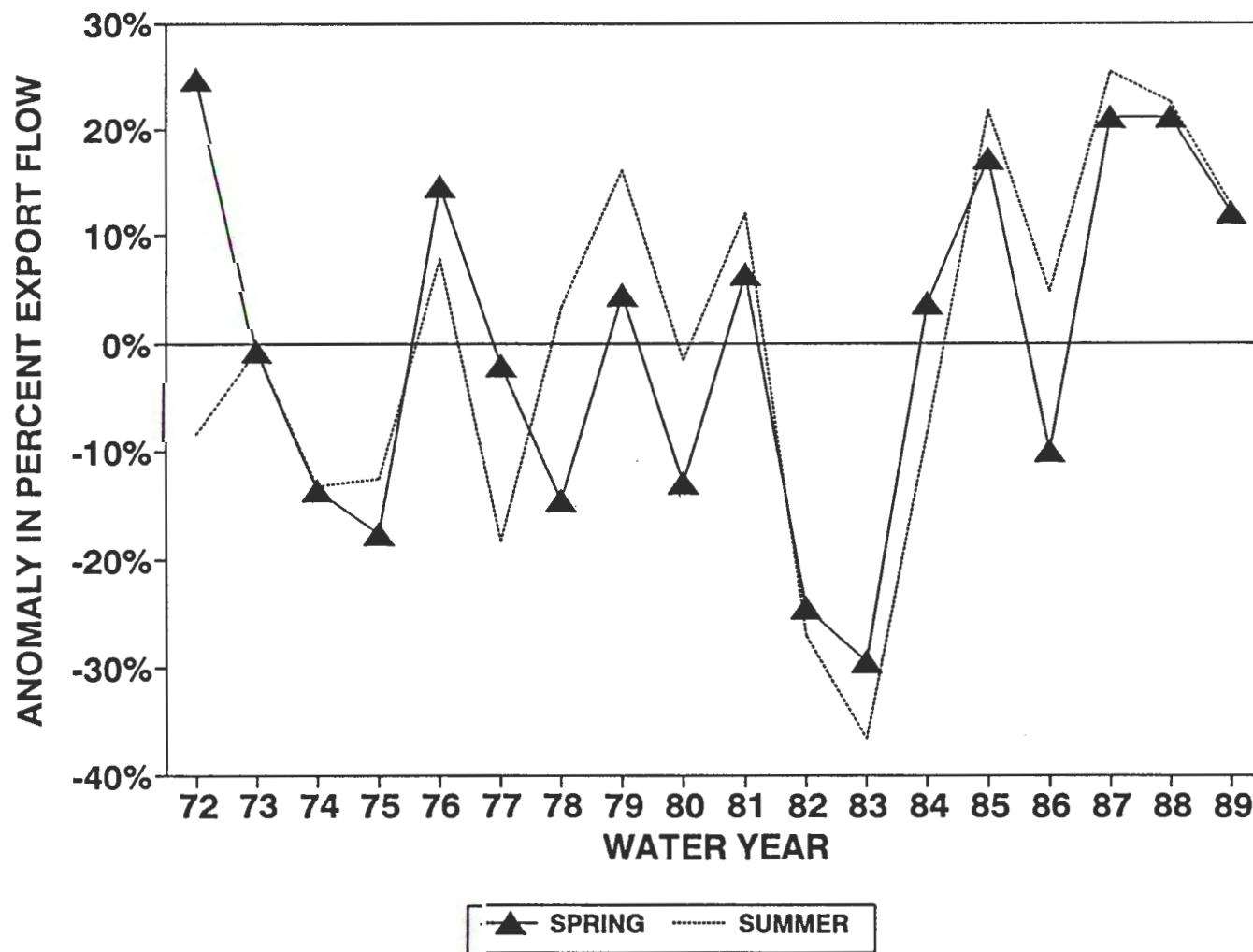
Figure 9.   Anomaly in percent export flows for spring and summer.
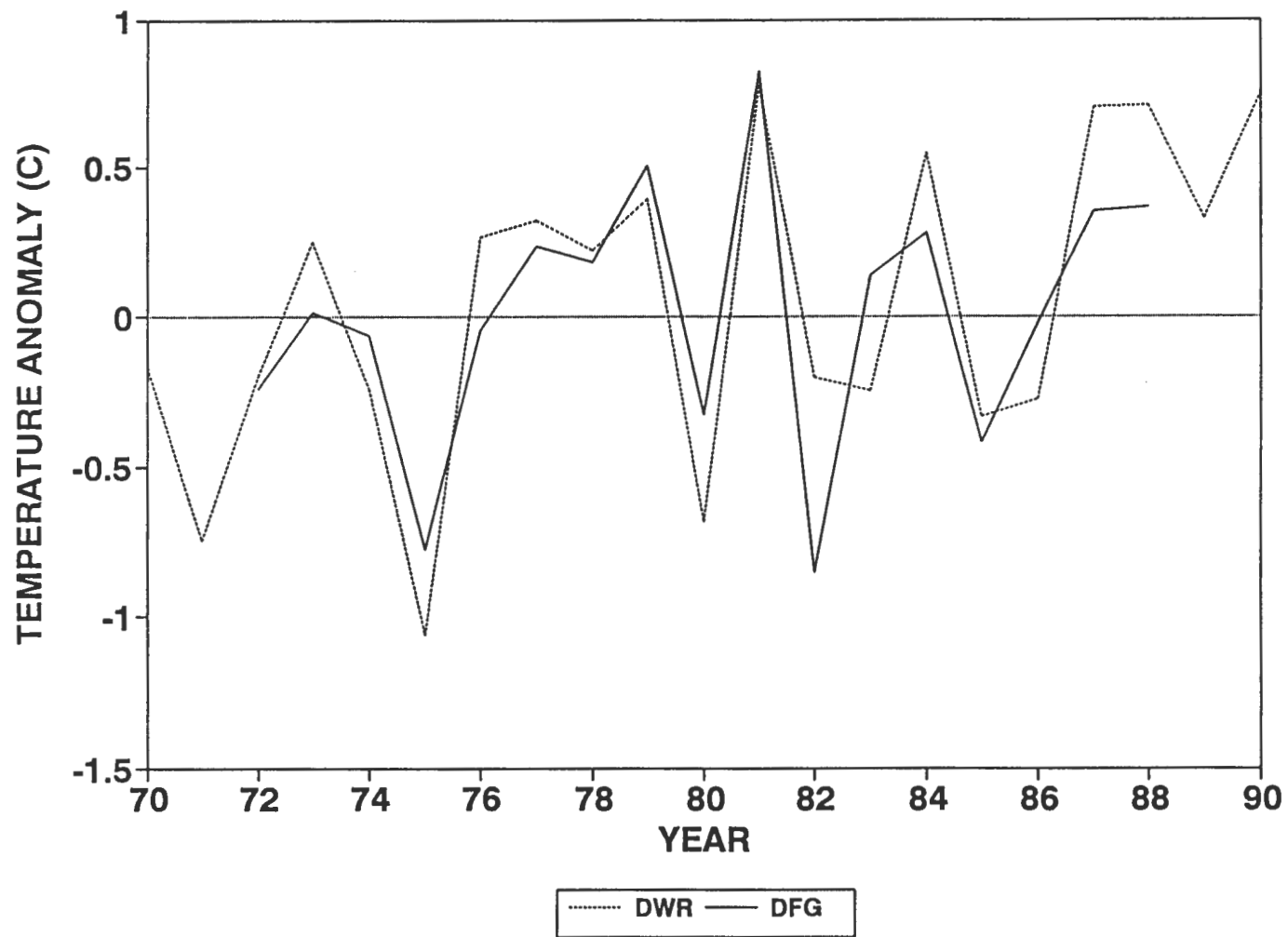
Figure 10. Anomalies in temperature, annual means from DWR and DFG data sets.
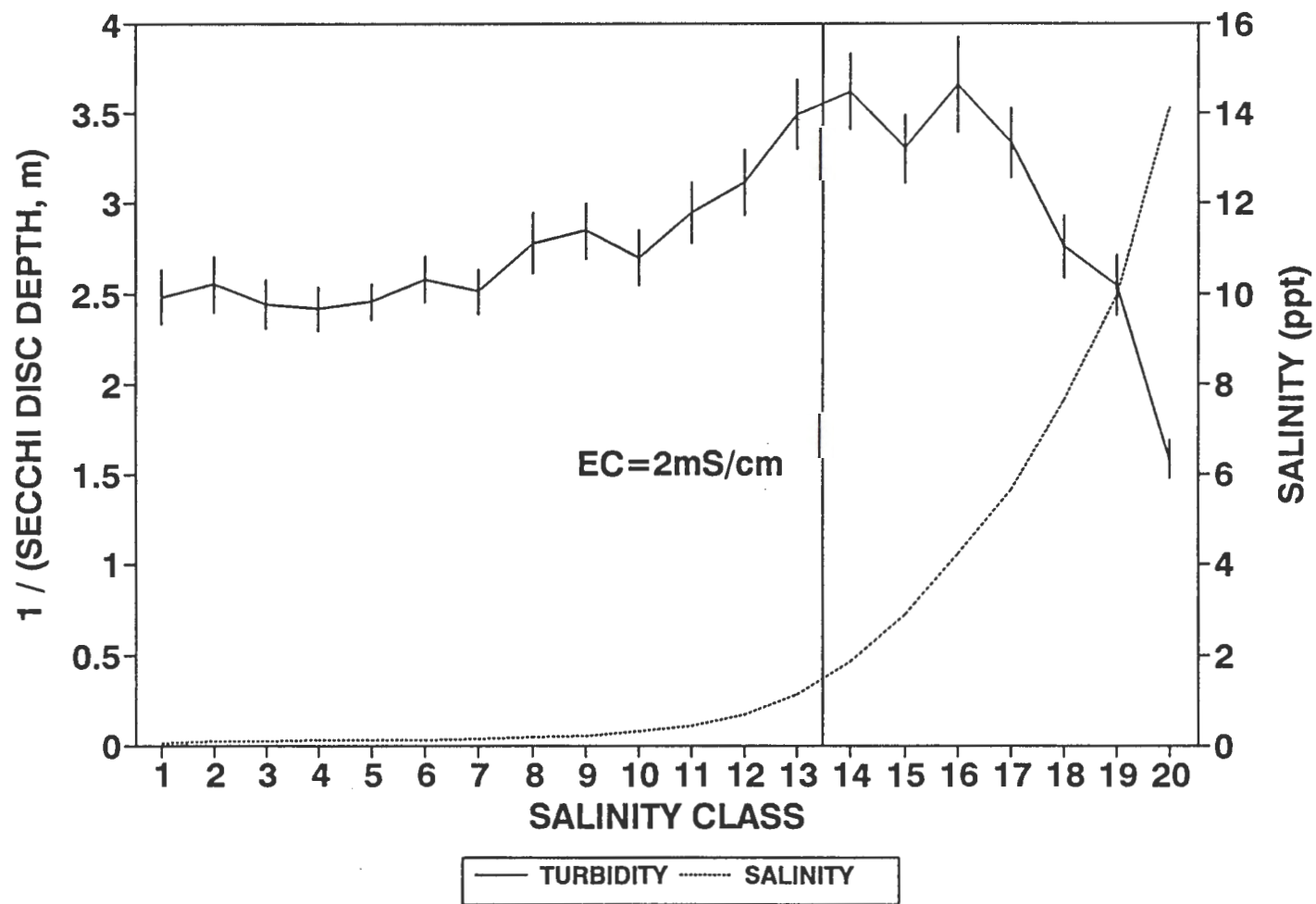
Figure 11. Turbidity measured as 1/Secchi disk depth vs. salinity class, mean and 95% confidence limits from DFG core dataset. The dashed line gives mean salinity in the class, and the vertical line is the upstream end of the entrapment zone by the operational definition.
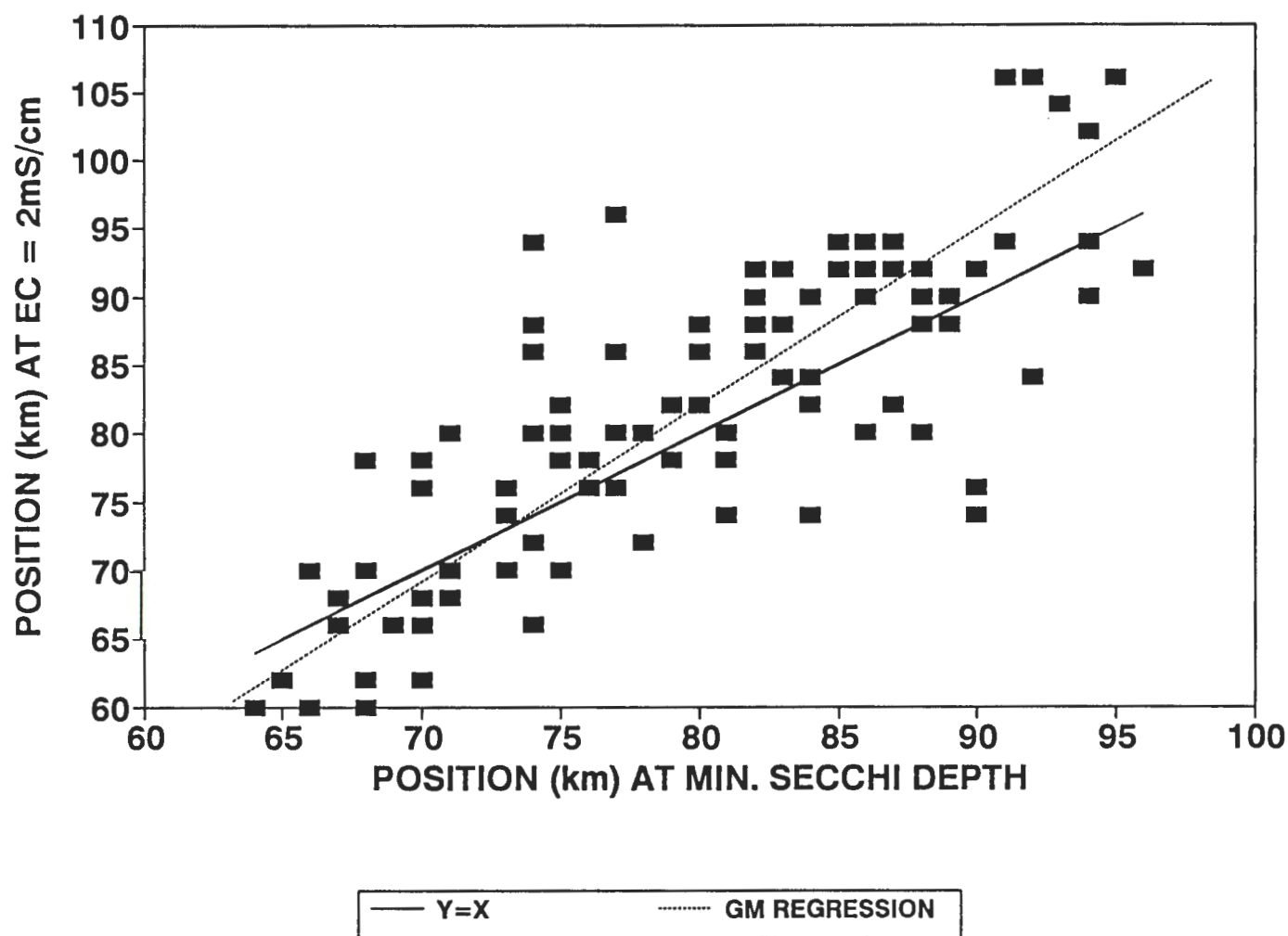
Figure 12. EZ position by the operational definition vs. position of the turbidity maximum. Each point is a monthly mean from the DFG dataset. Solid line is for both definitions identical, dashed line is the geometric mean regression.

Figure 13. EZ position by the operational definition vs. log Delta outflow, monthly means.
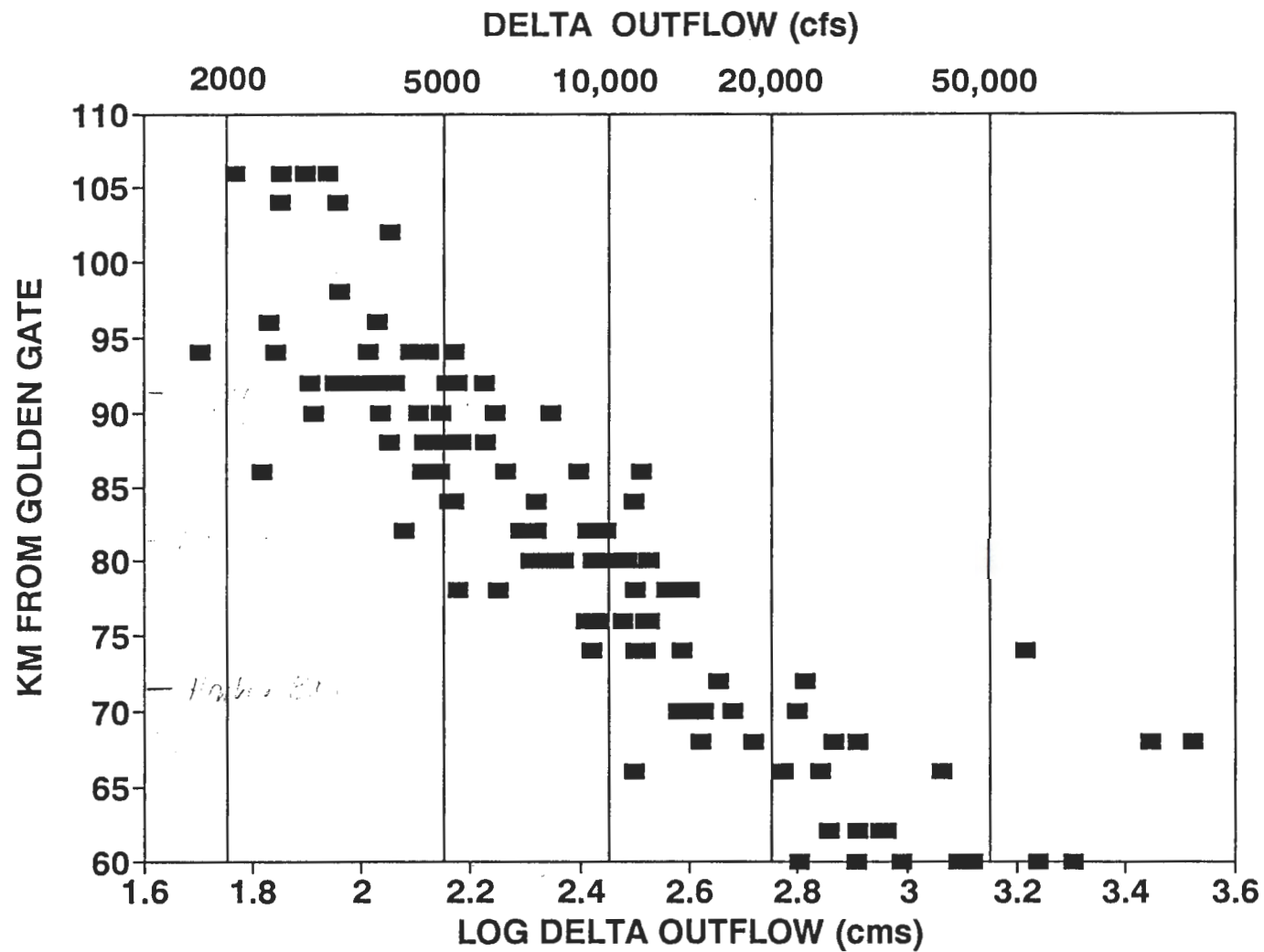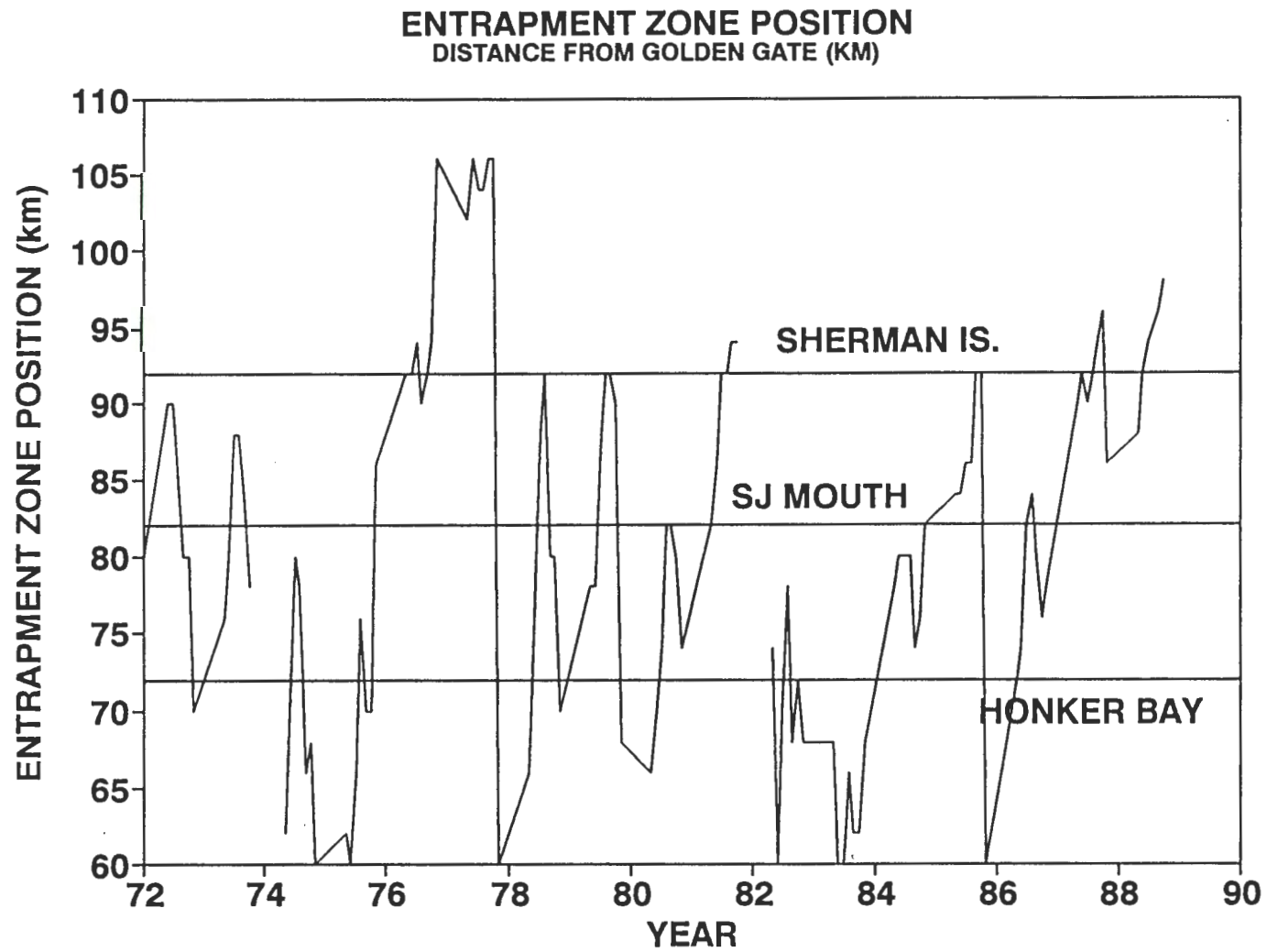
Figure 14. Entrapment zone position vs. time.
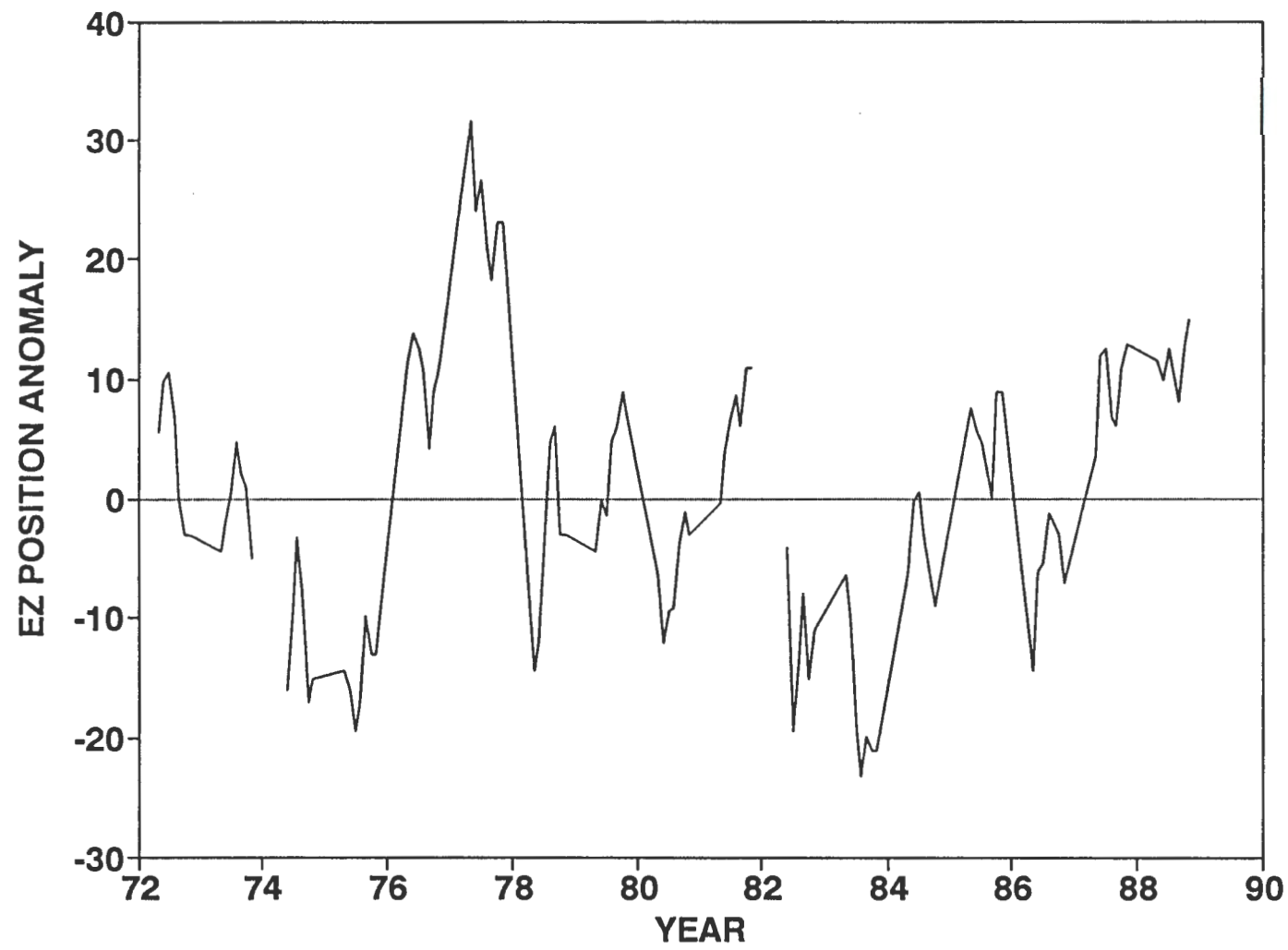
Figure 15. Anomaly in entrapment zone position vs. time.
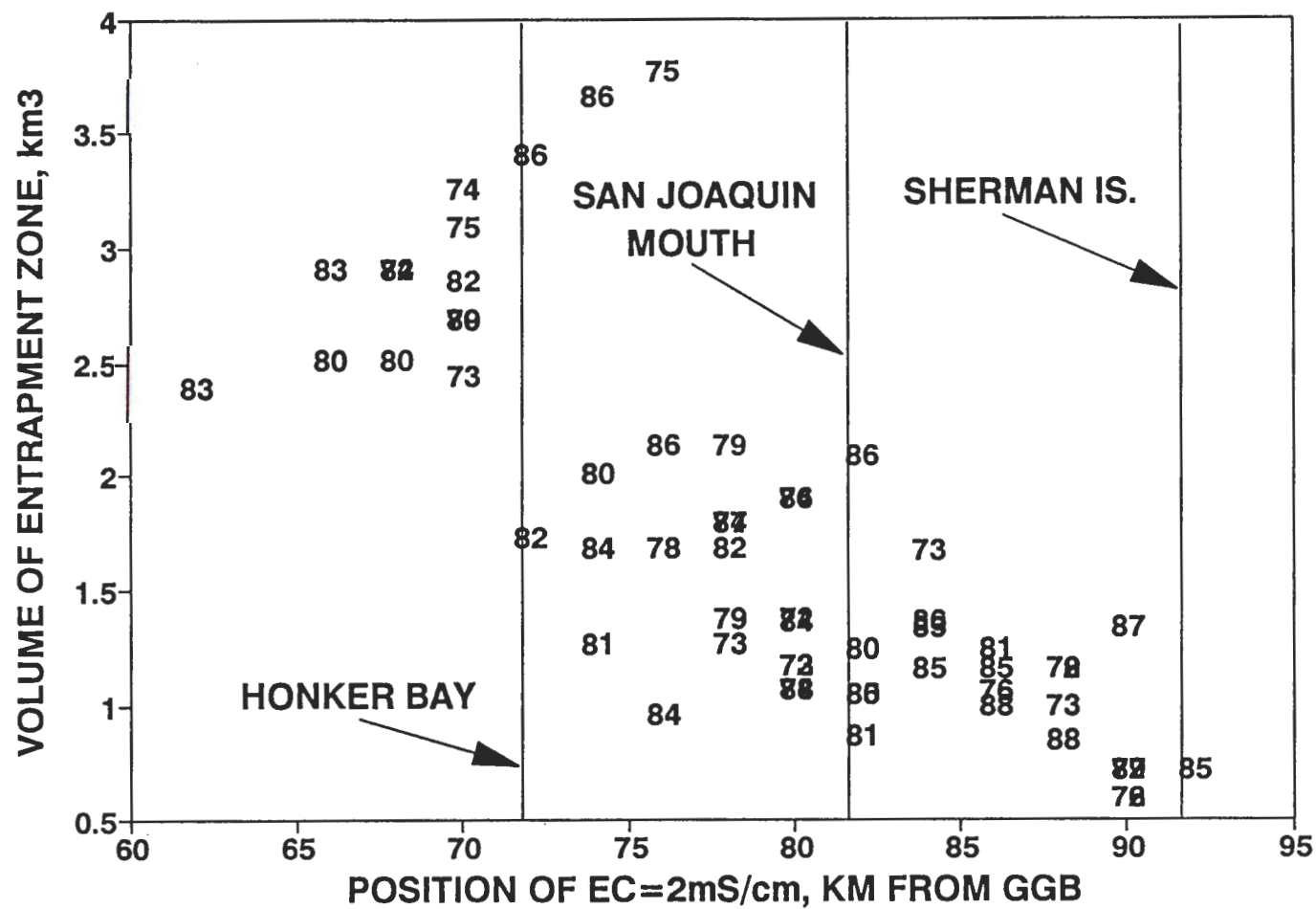
Figure 16. Volume of the entrapment zone, defined as the area with a salinity of 1-6, vs. EZ position by the operational definition.
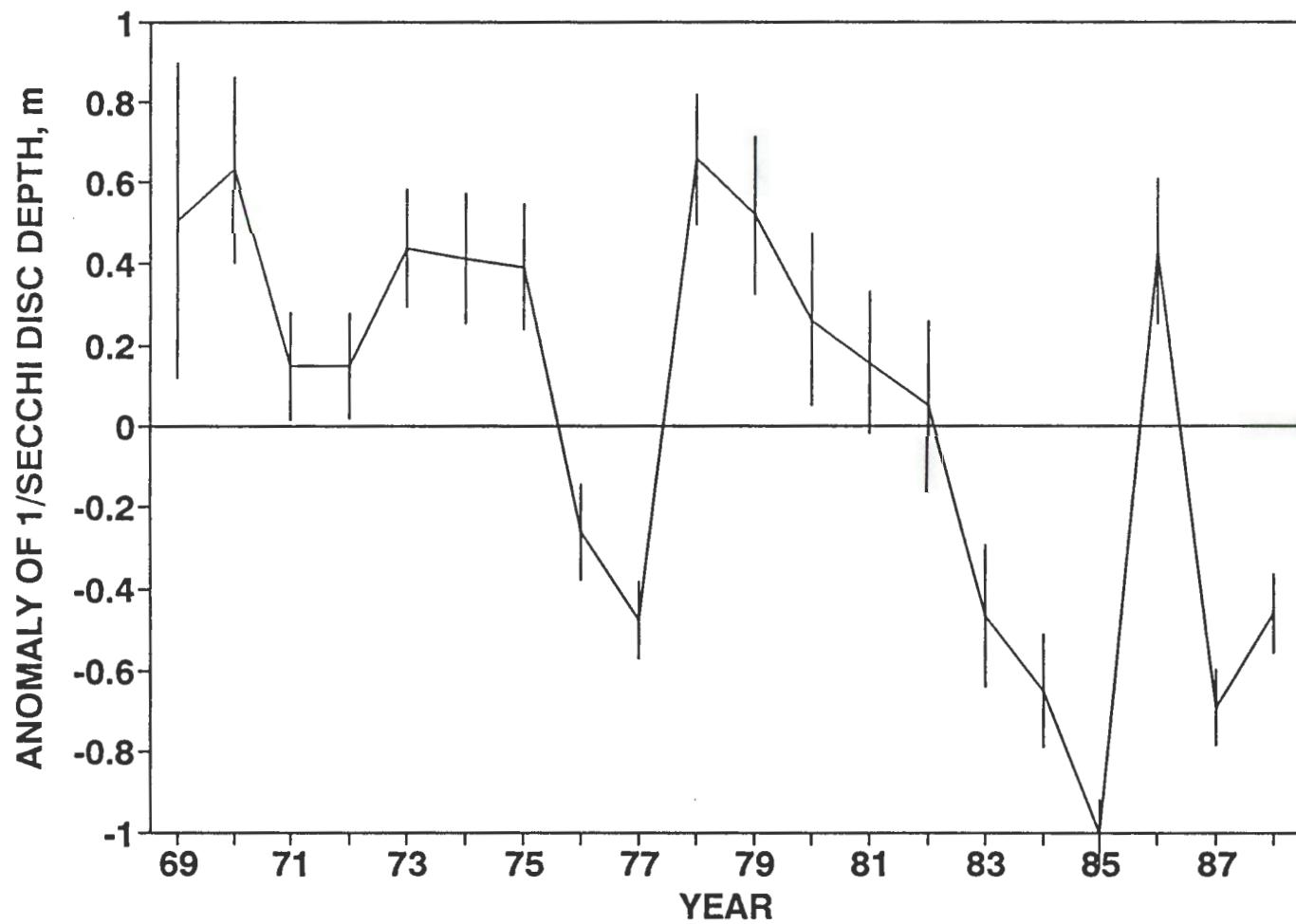
Figure 17. Anomalies in turbidity as 1/Secchi disk depth, annual mean and 95% confidence limits.
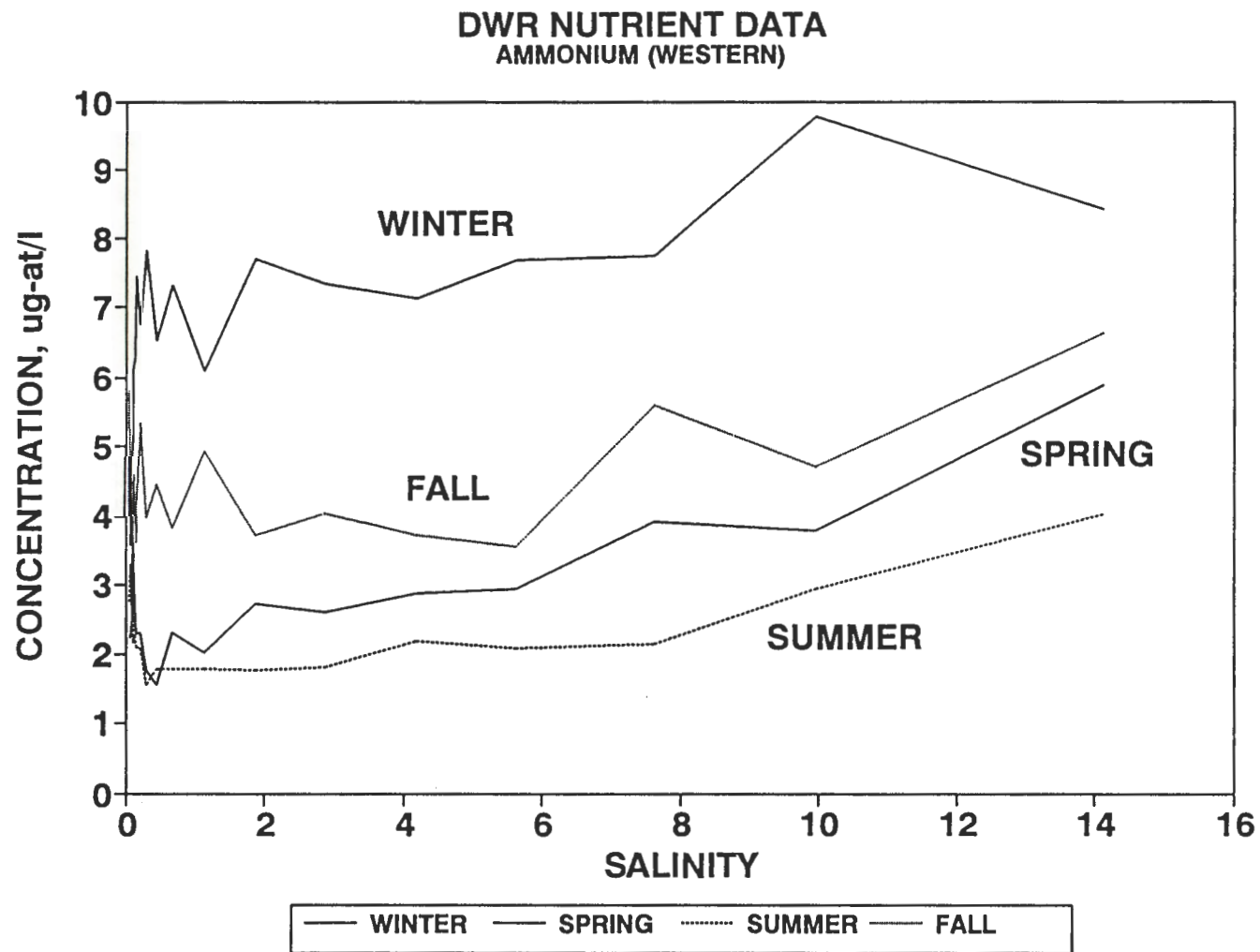
Figure 18. Ammonium concentration vs. salinity by season.

DWR NUTRIENT DATA
NITRATE (WESTERN)

WINTER

SPRING

FALL

SUMMER

CONCENTRATION, ug-at/l

SALINITY

WINTER — SPRING ·········· SUMMER — FALL
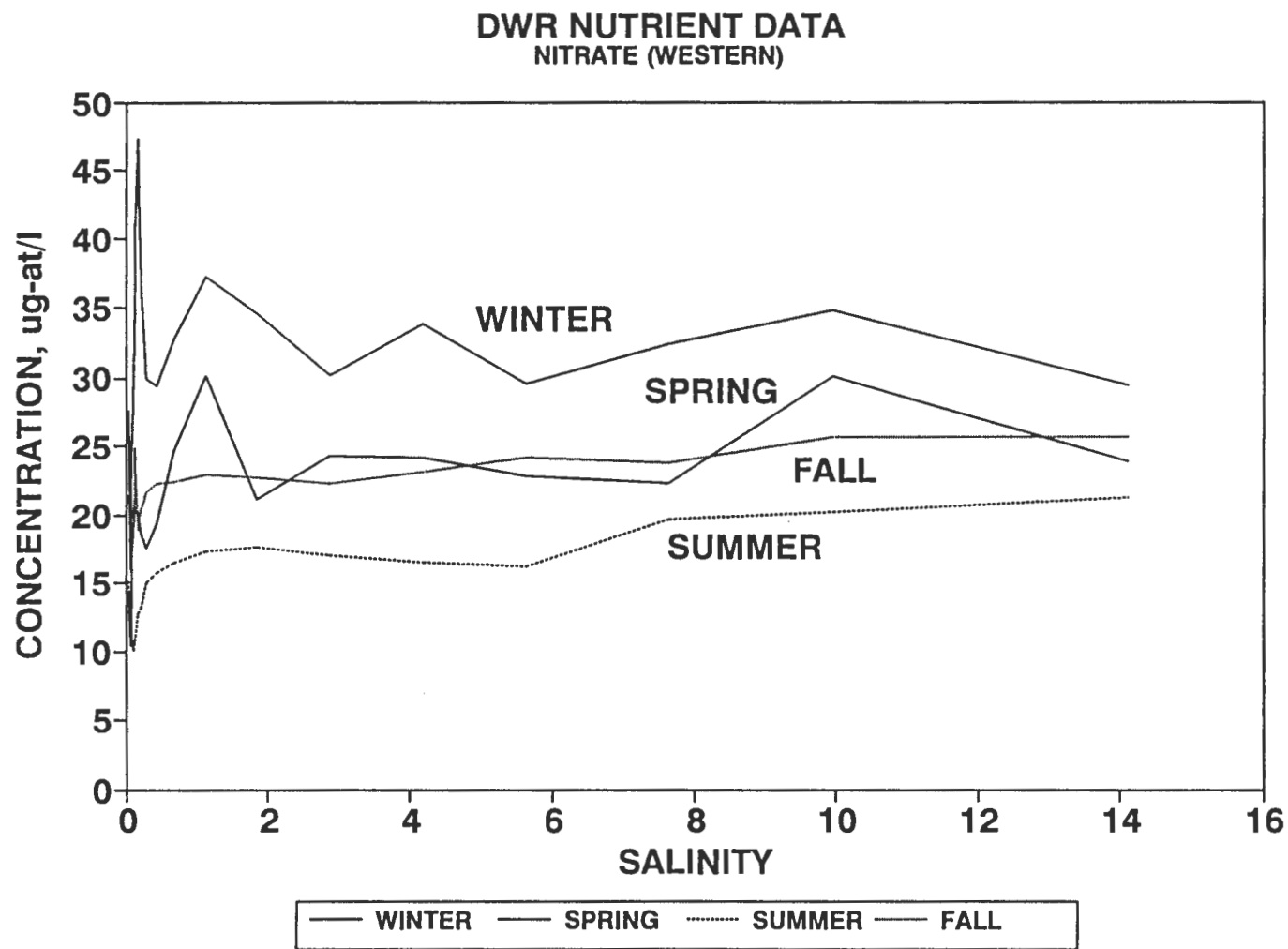
Figure 19. Nitrate concentration vs. salinity by season.
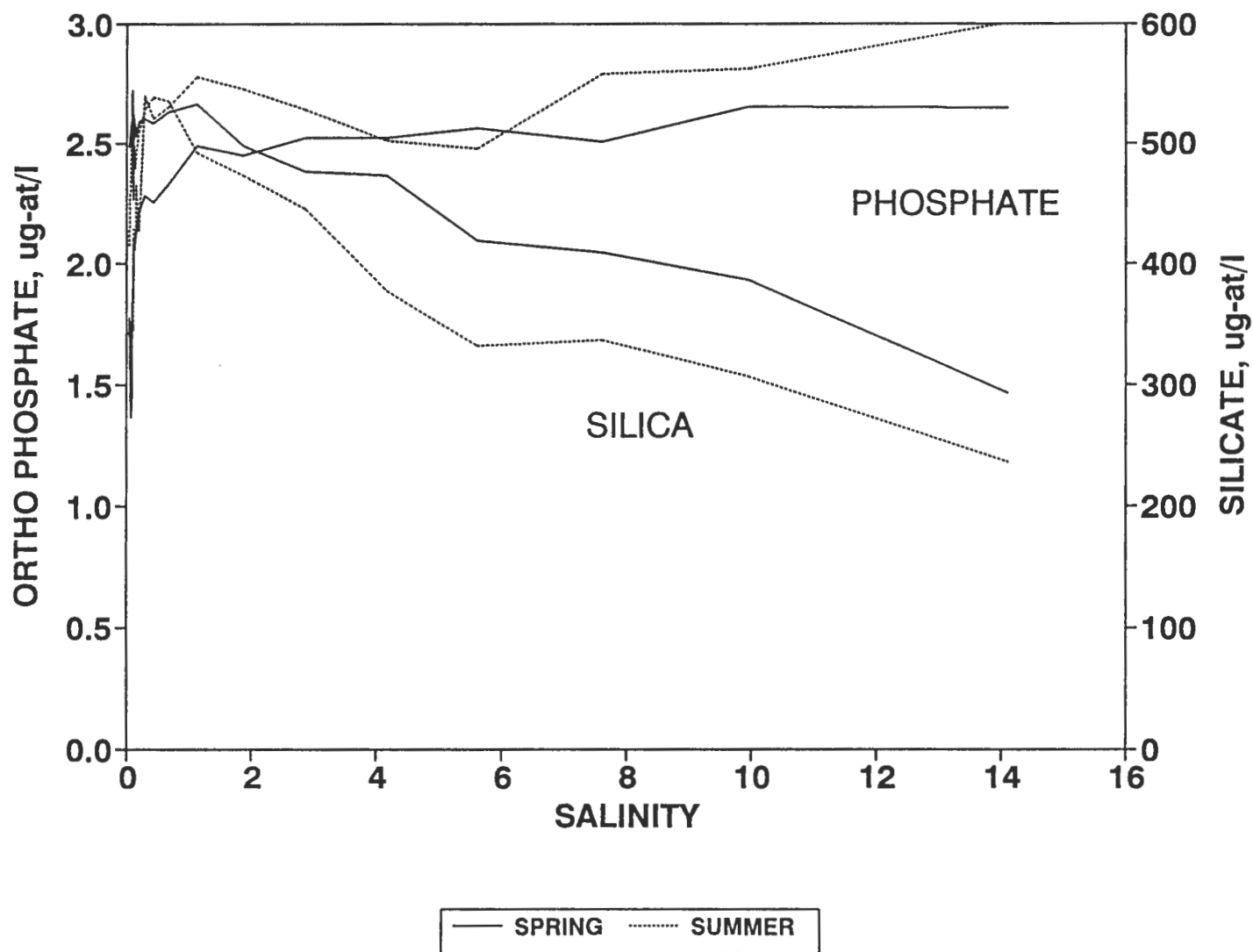
Figure 20.   Ortho phosphate and silicate concentrations vs. salinity for spring and summer.
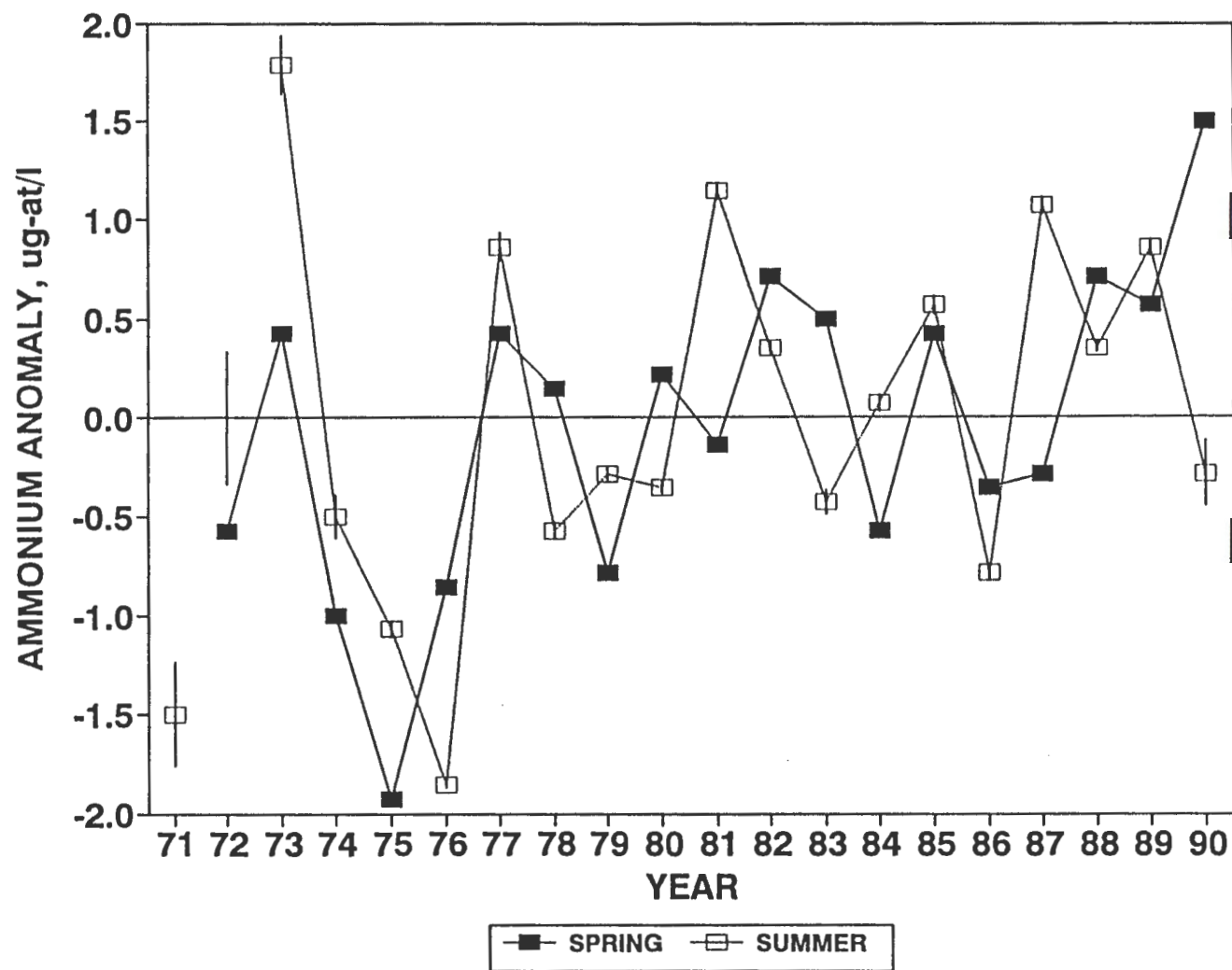
Figure 21. Ammonium concentration anomaly vs. time for spring and summer, seasonal means and 95% confidence limits for summer only.
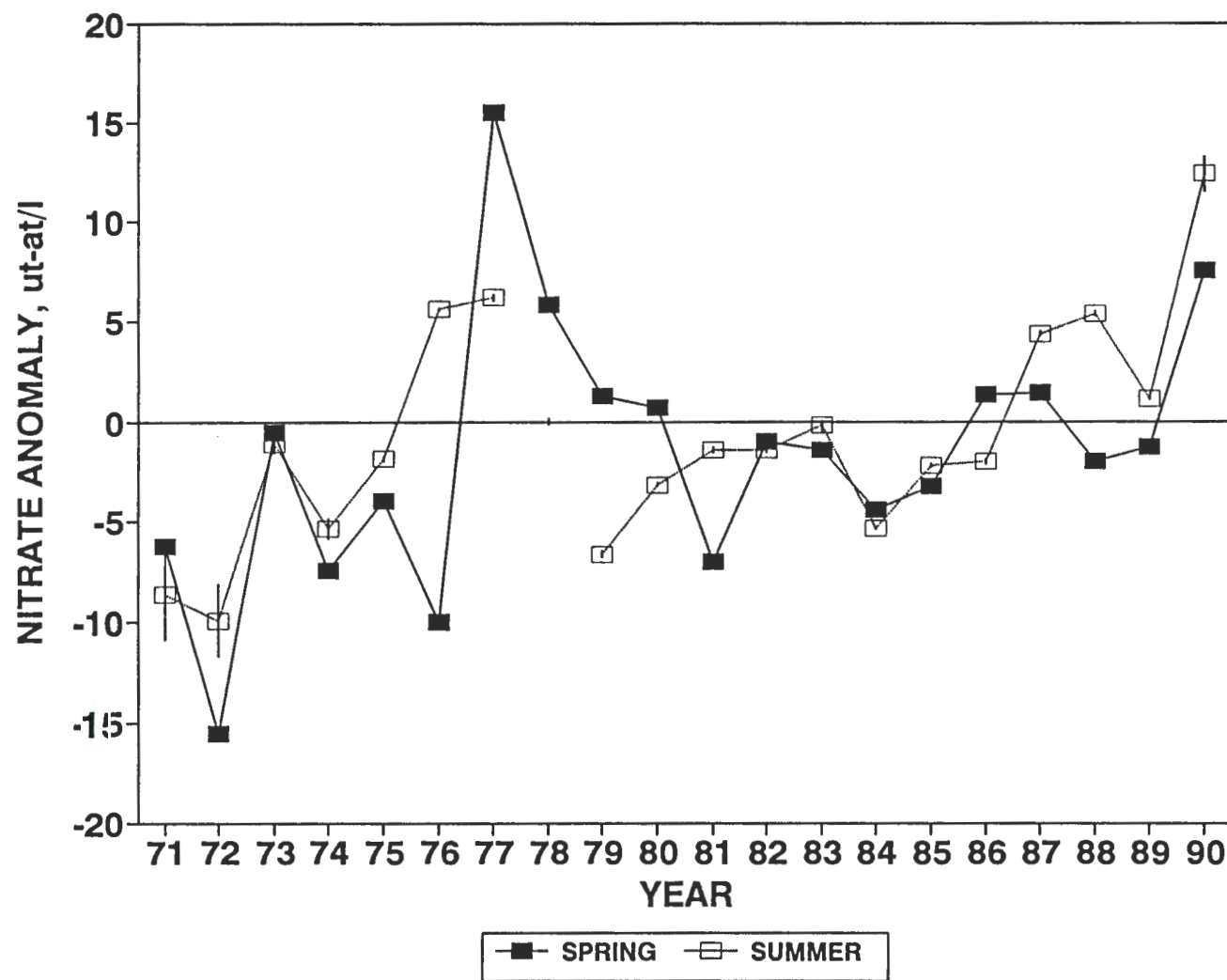
Figure 22. Nitrate concentration anomaly vs. time for spring and summer, seasonal means and 95% confidence limits for summer only.
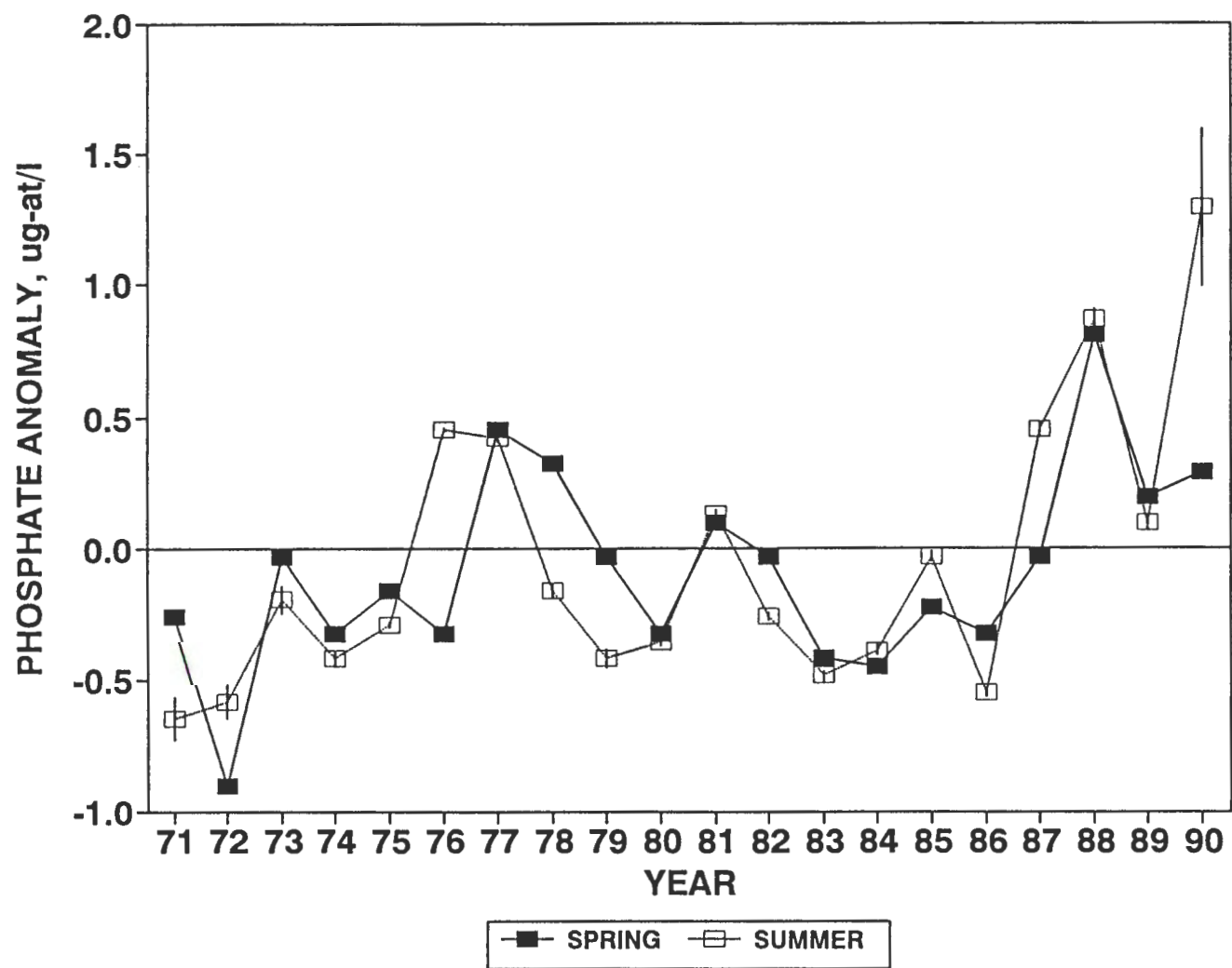
Figure 23. Ortho phosphate concentration anomaly vs. time for spring and summer, seasonal means and 95% confidence limits for summer only.
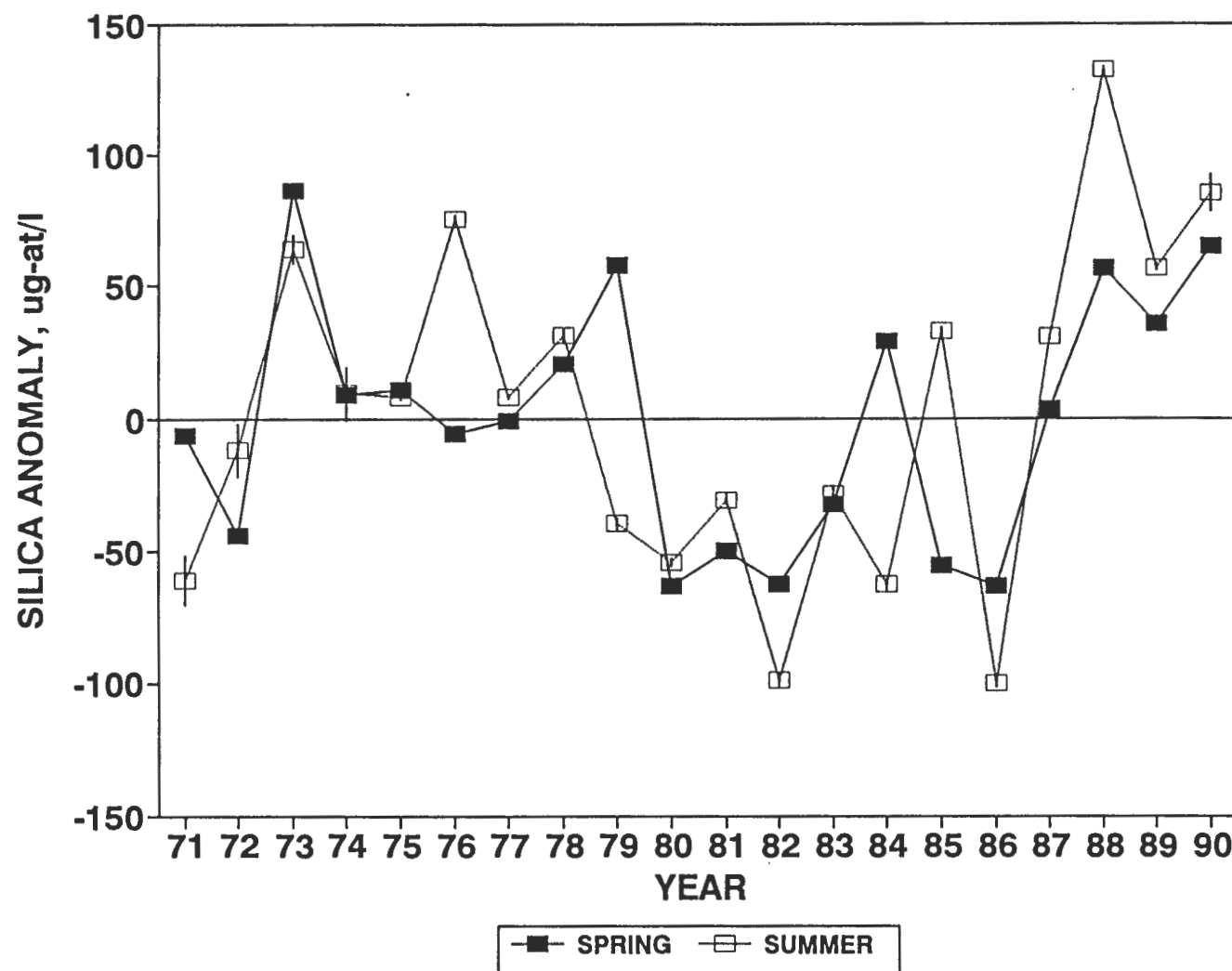
Figure 24. Silicate concentration anomaly vs. time for spring and summer, seasonal means and 95% confidence limits for summer only.
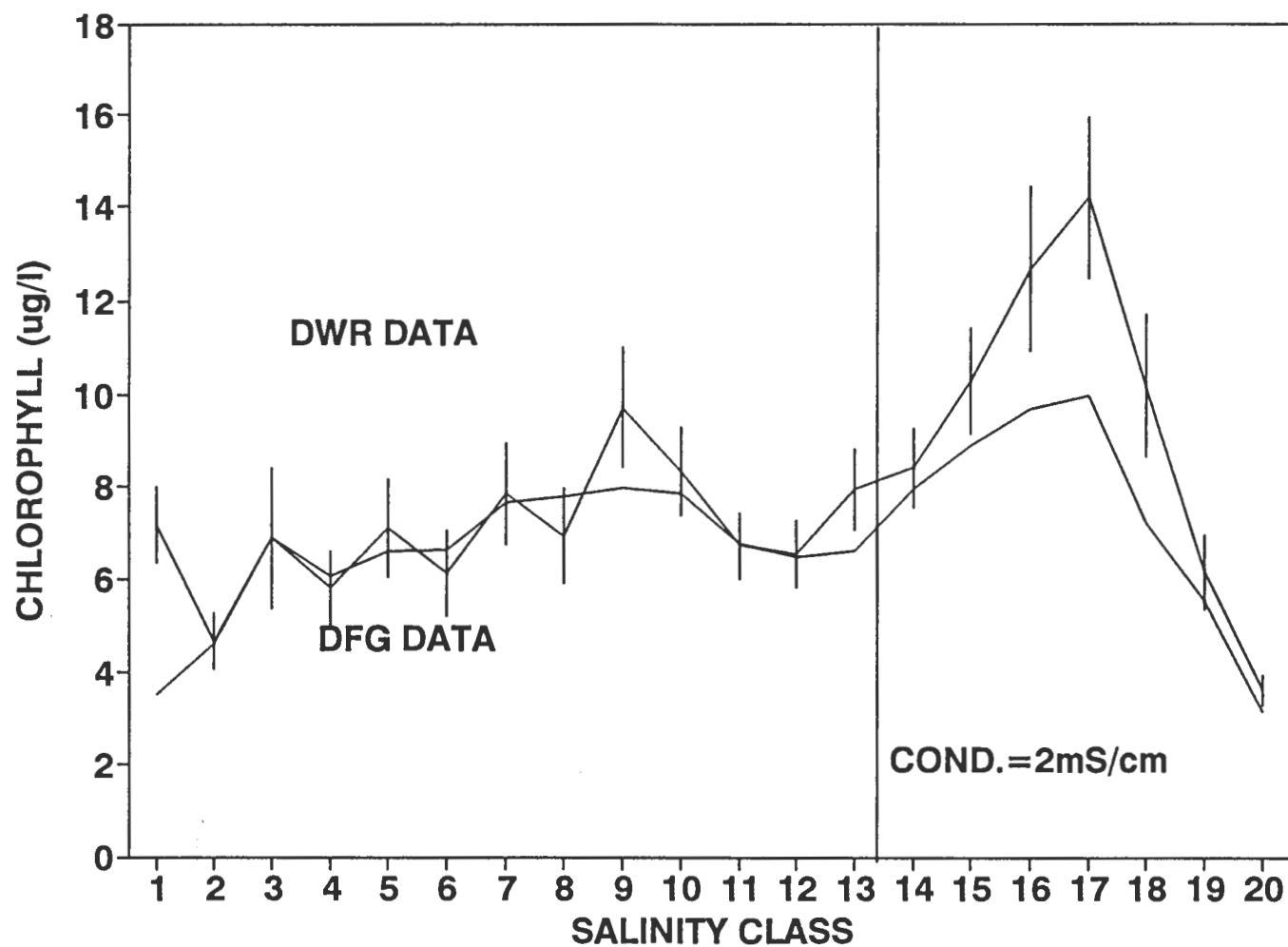
Figure 25. Chlorophyll concentrations vs. salinity class from DWR (with error bars for 95% confidence limits) and DFG data, mean values.
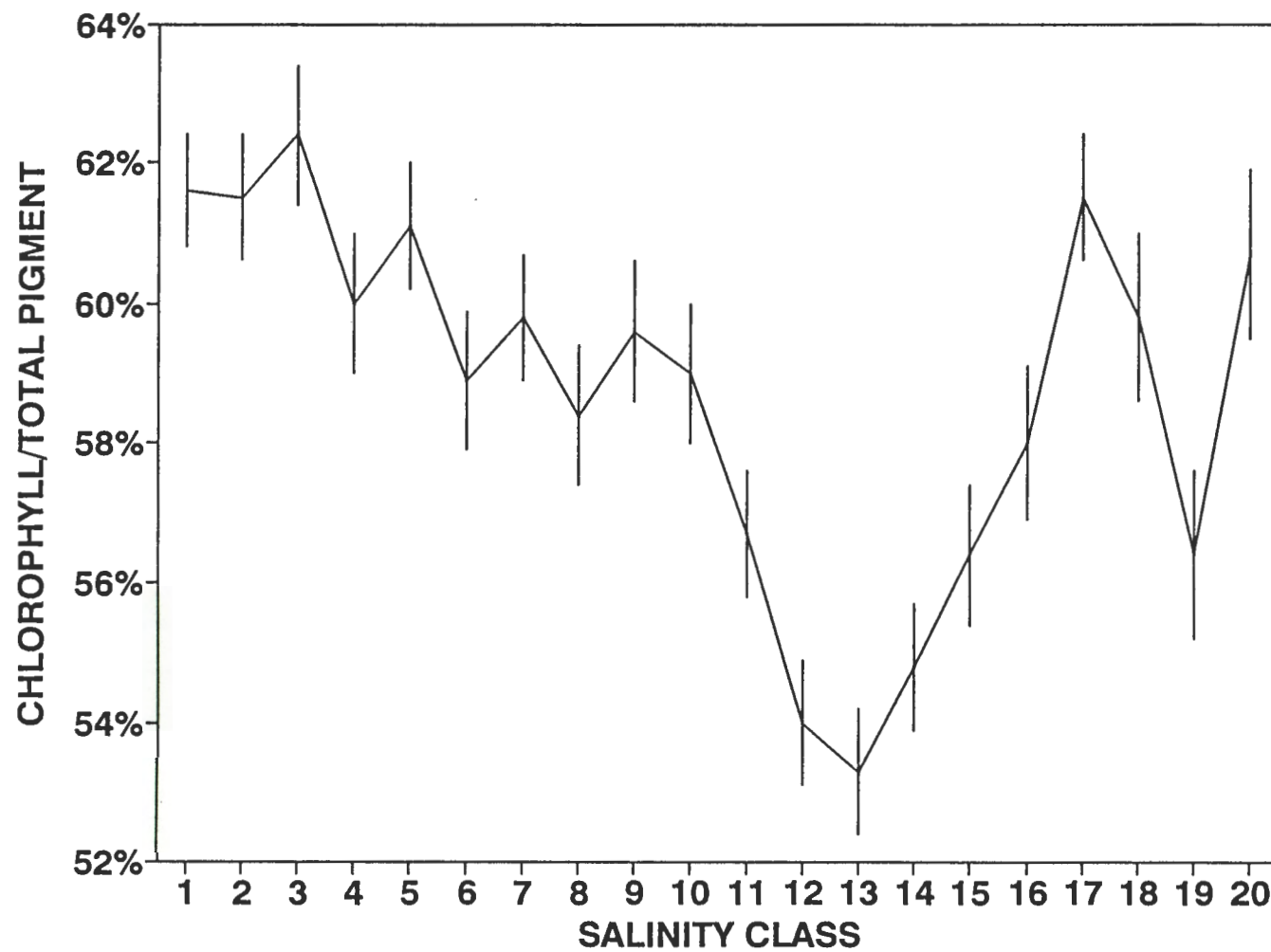
Figure 26. Ratio of chlorophyll to total pigment (chlorophyll plus phaeopigments) vs. salinity class in the DWR dataset, means and 95% confidence intervals.
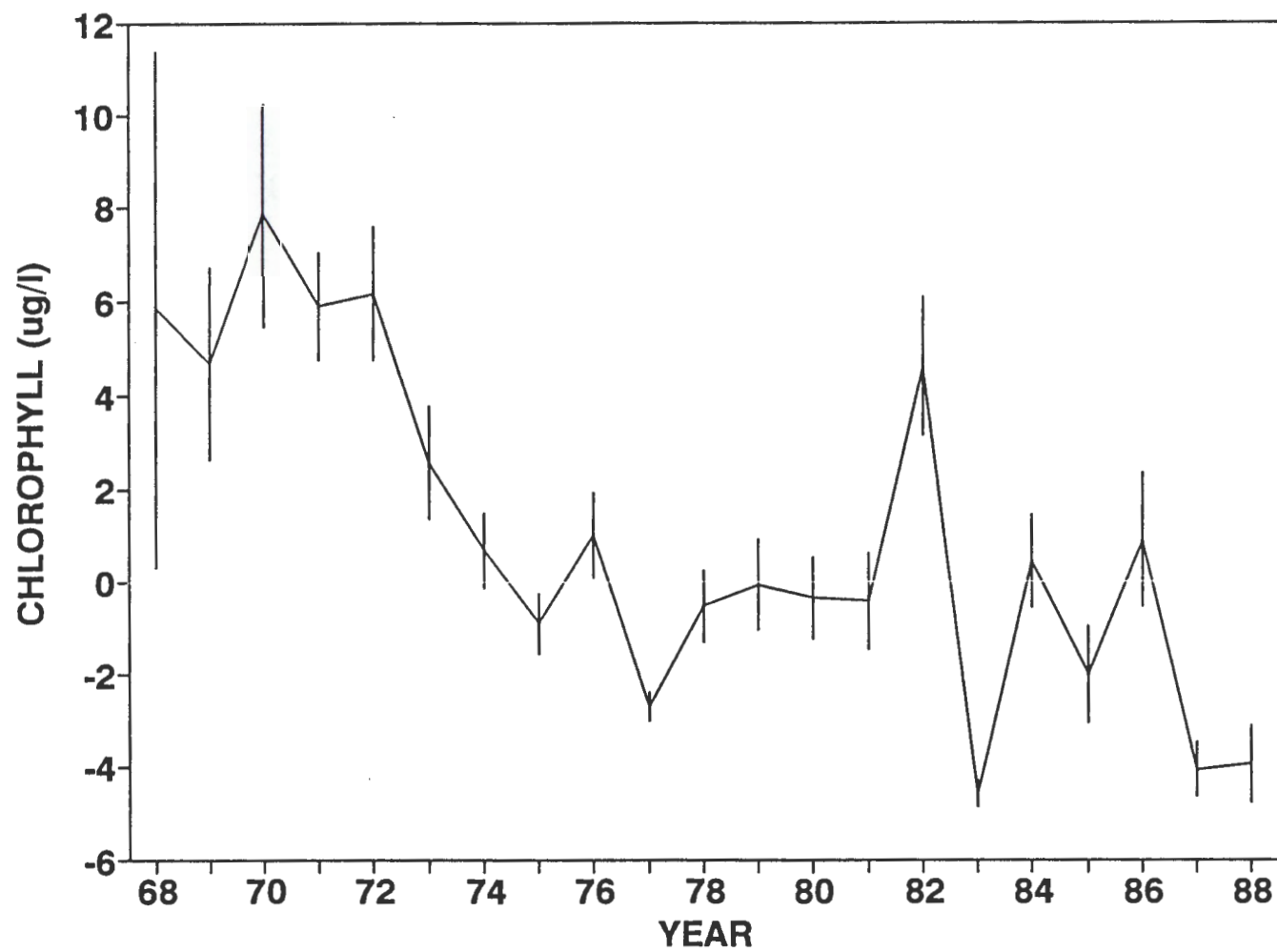
Figure 27. Time trend in chlorophyll anomaly vs. time, annual mean and 95% confidence limits from DWR dataset.
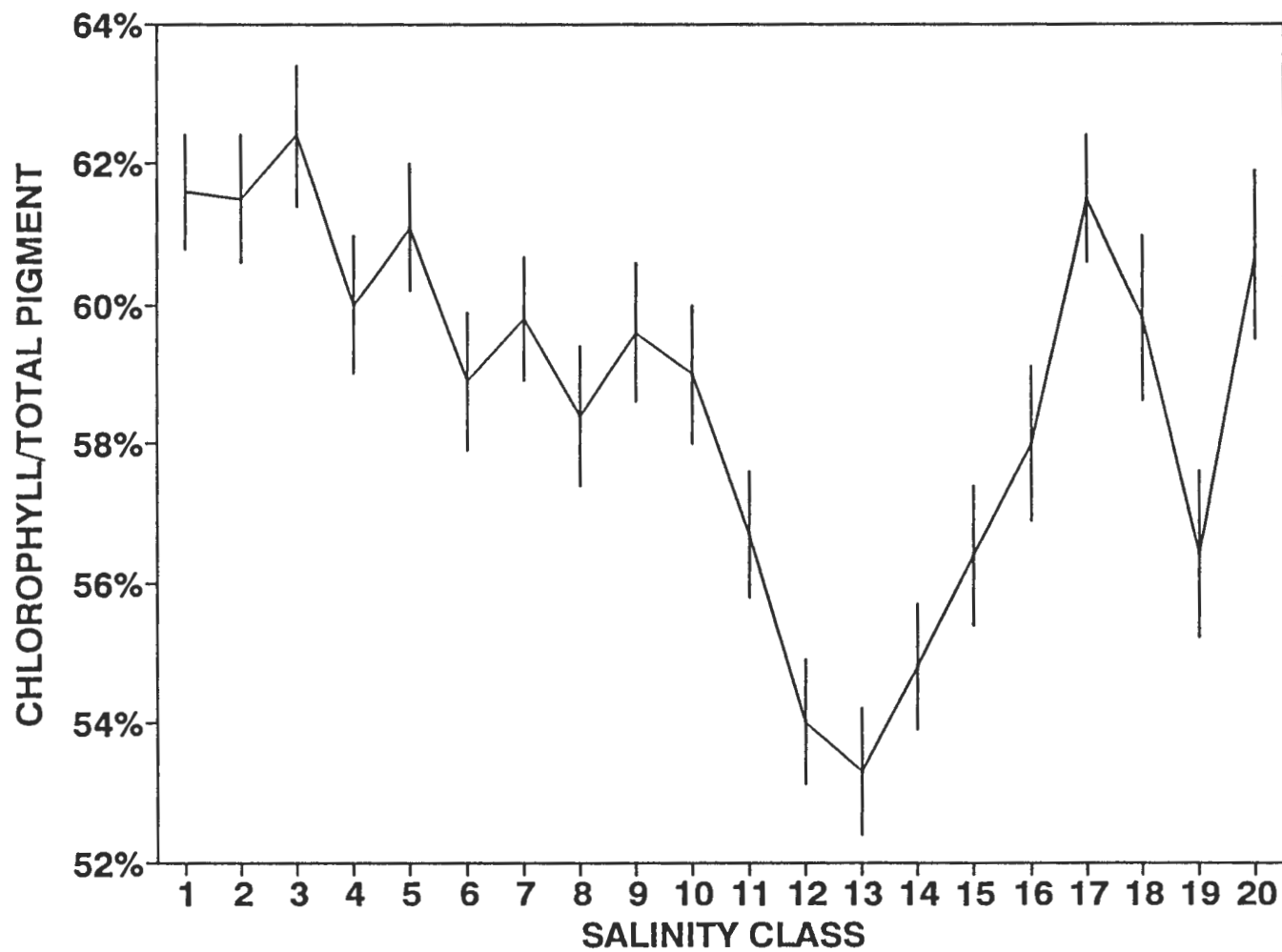
Figure 28. Time trend in the ratio of chlorophyll to total pigment vs. time, annual mean and 95% confidence limits from DWR dataset.
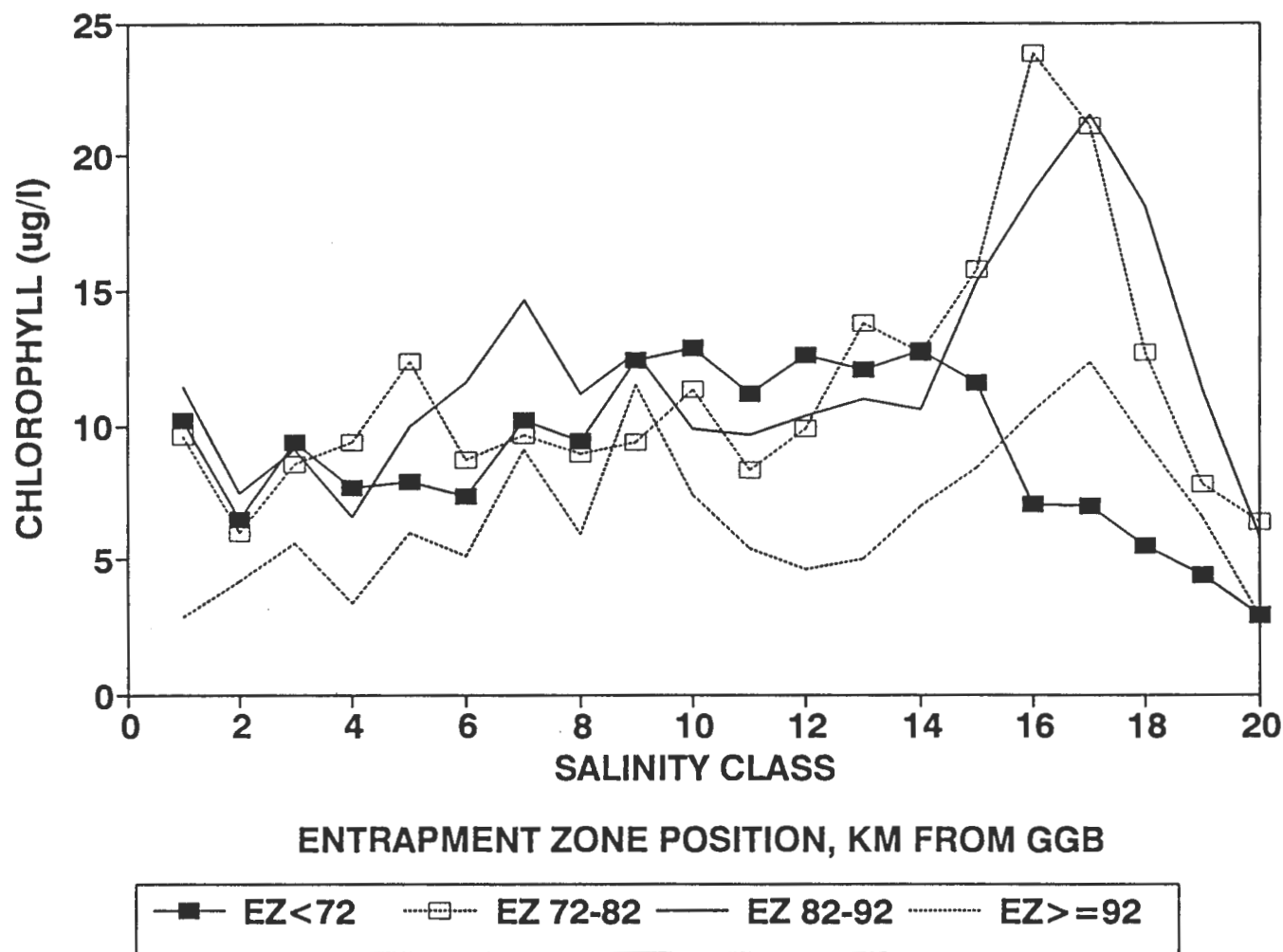
Figure 29. Chlorophyll vs. salinity class for 4 categories of entrapment zone position by the operational definition. The vertical bar at the left is the mean 95% confidence interval for a single value.
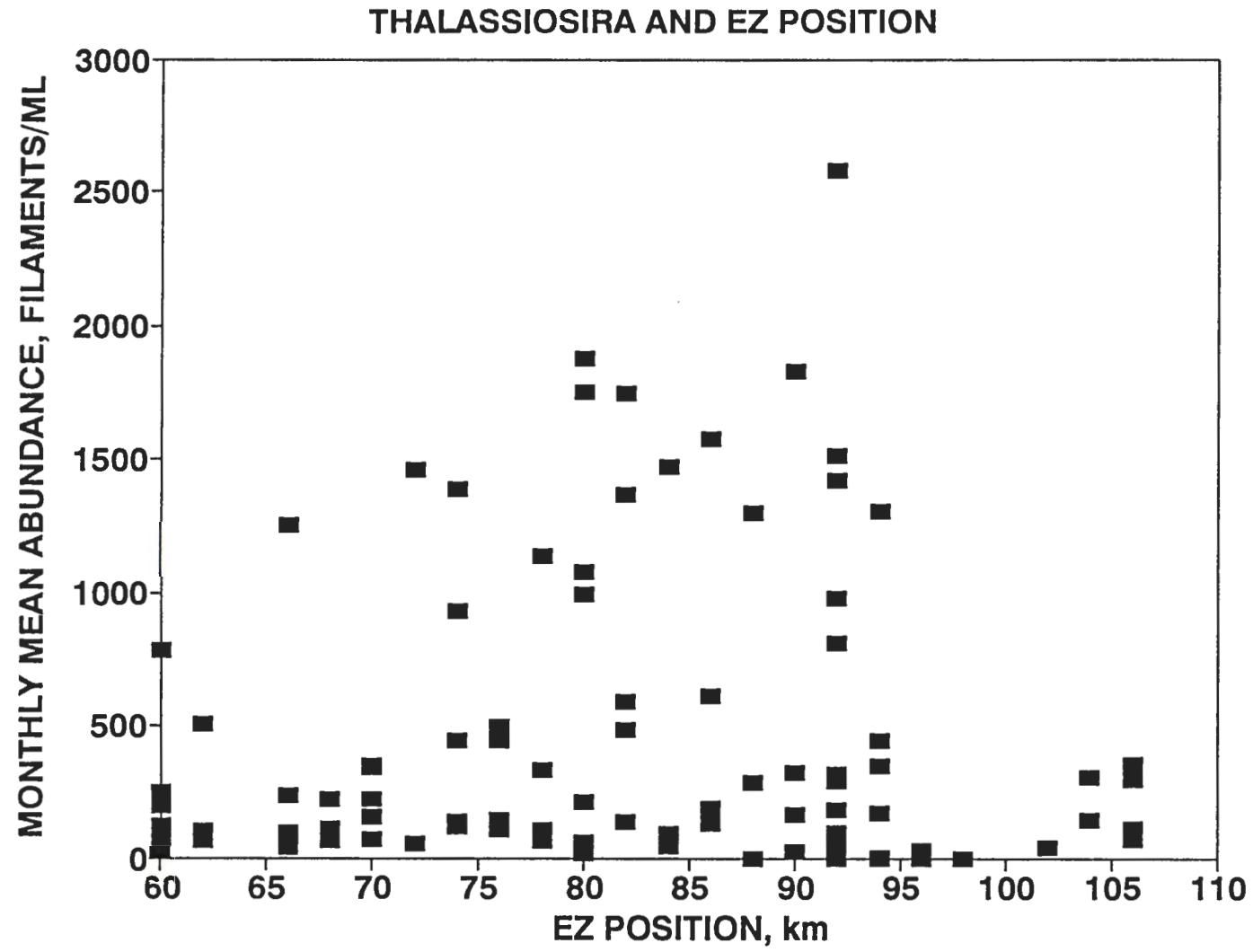
Figure 30. *Thalassiosira* spp. Monthly mean abundance vs. EZ position. Zeros have been eliminated.
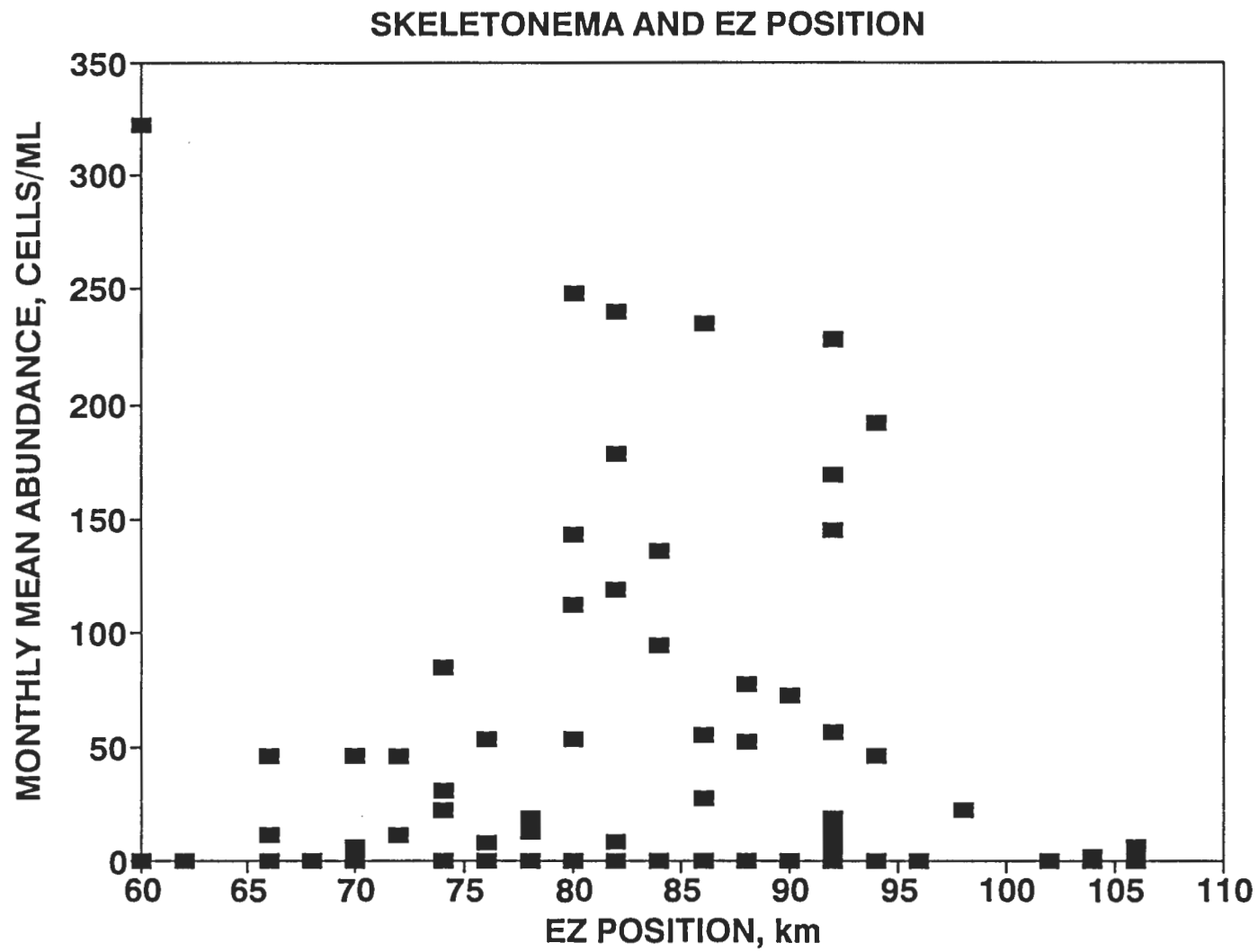
Figure 31. *Skeletonema costatum.* Monthly mean abundance vs. EZ position. Zeros have been eliminated.
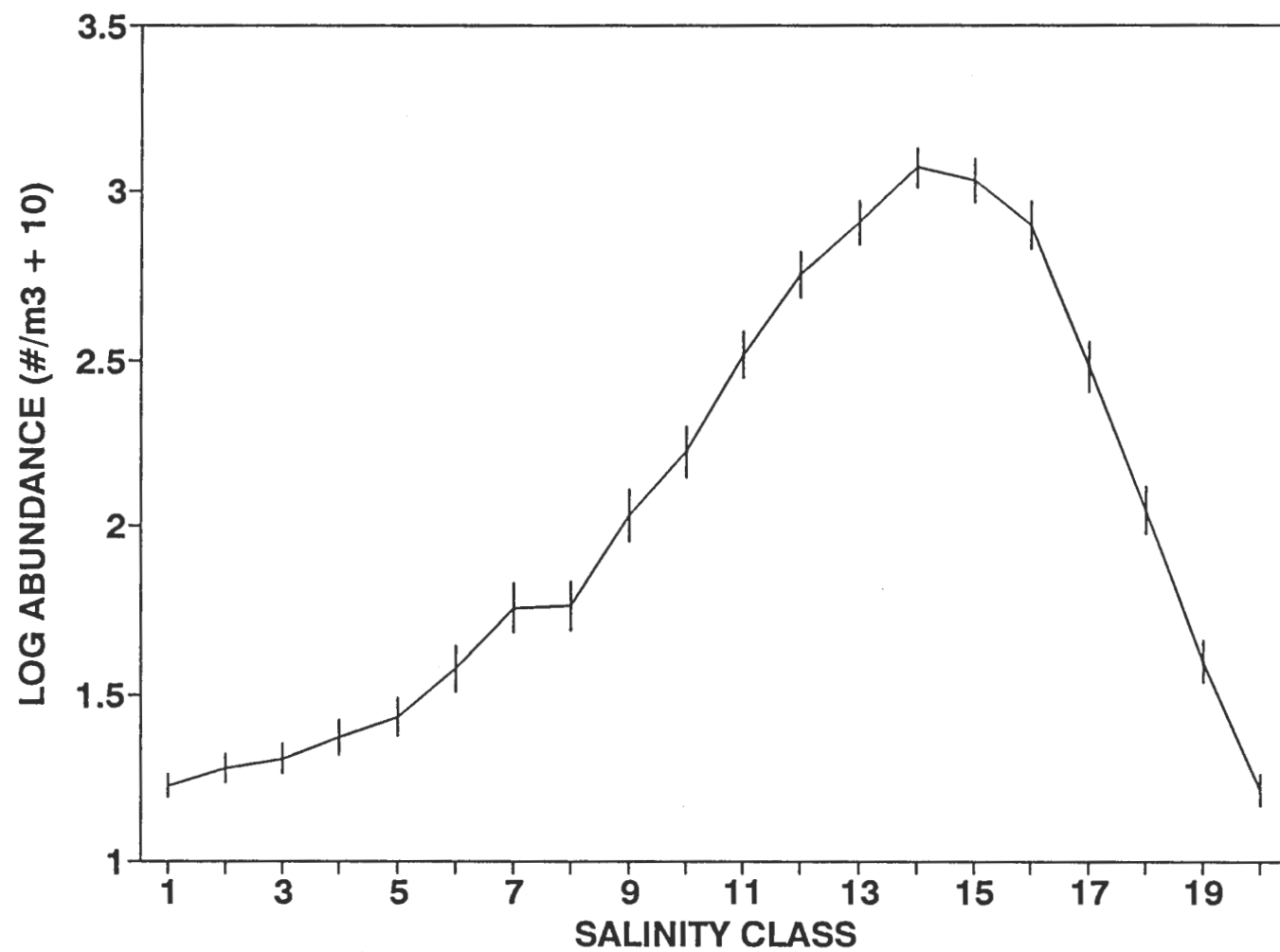
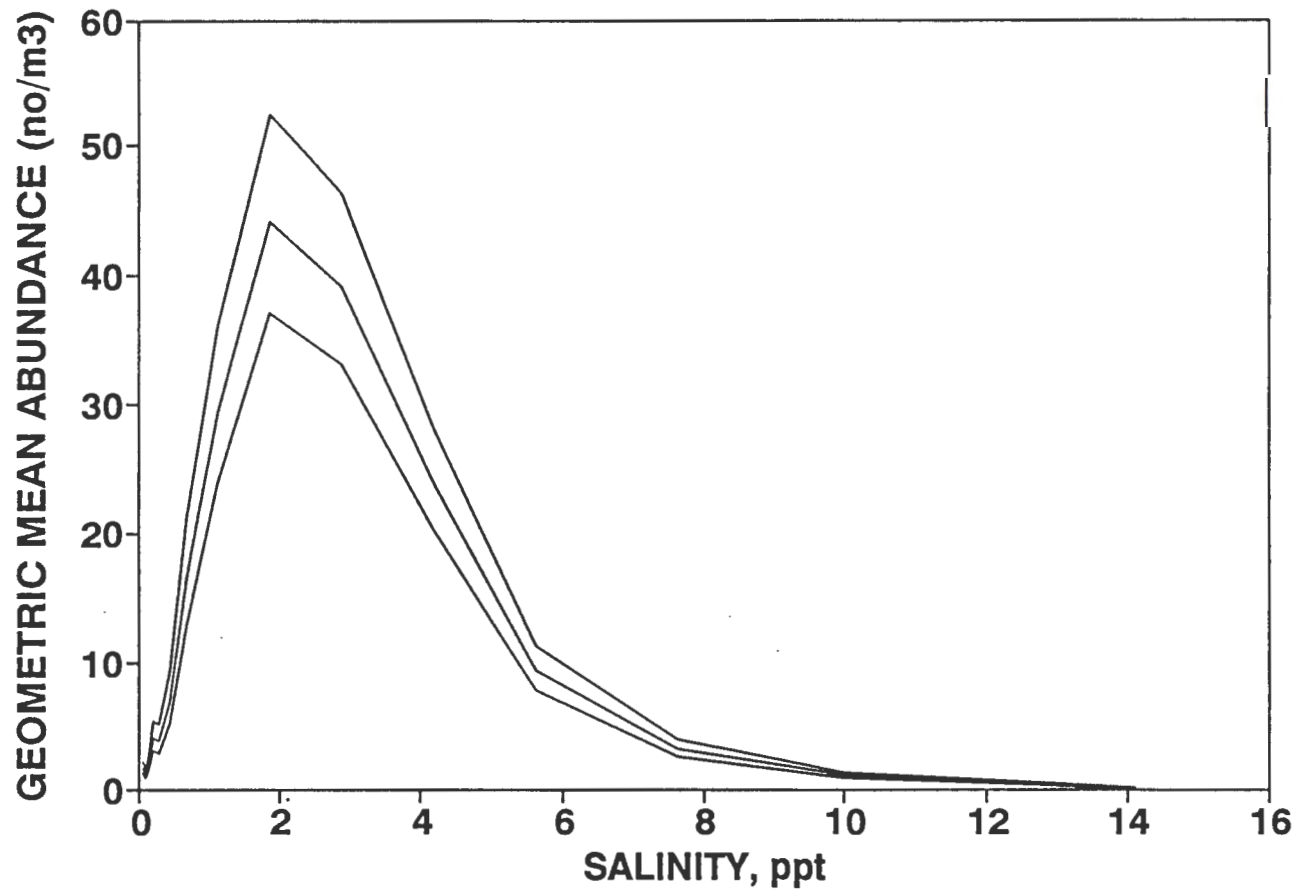**Figure 32.** *Eurytemora affinis.* Mean and 95% confidence intervals by salinity class.
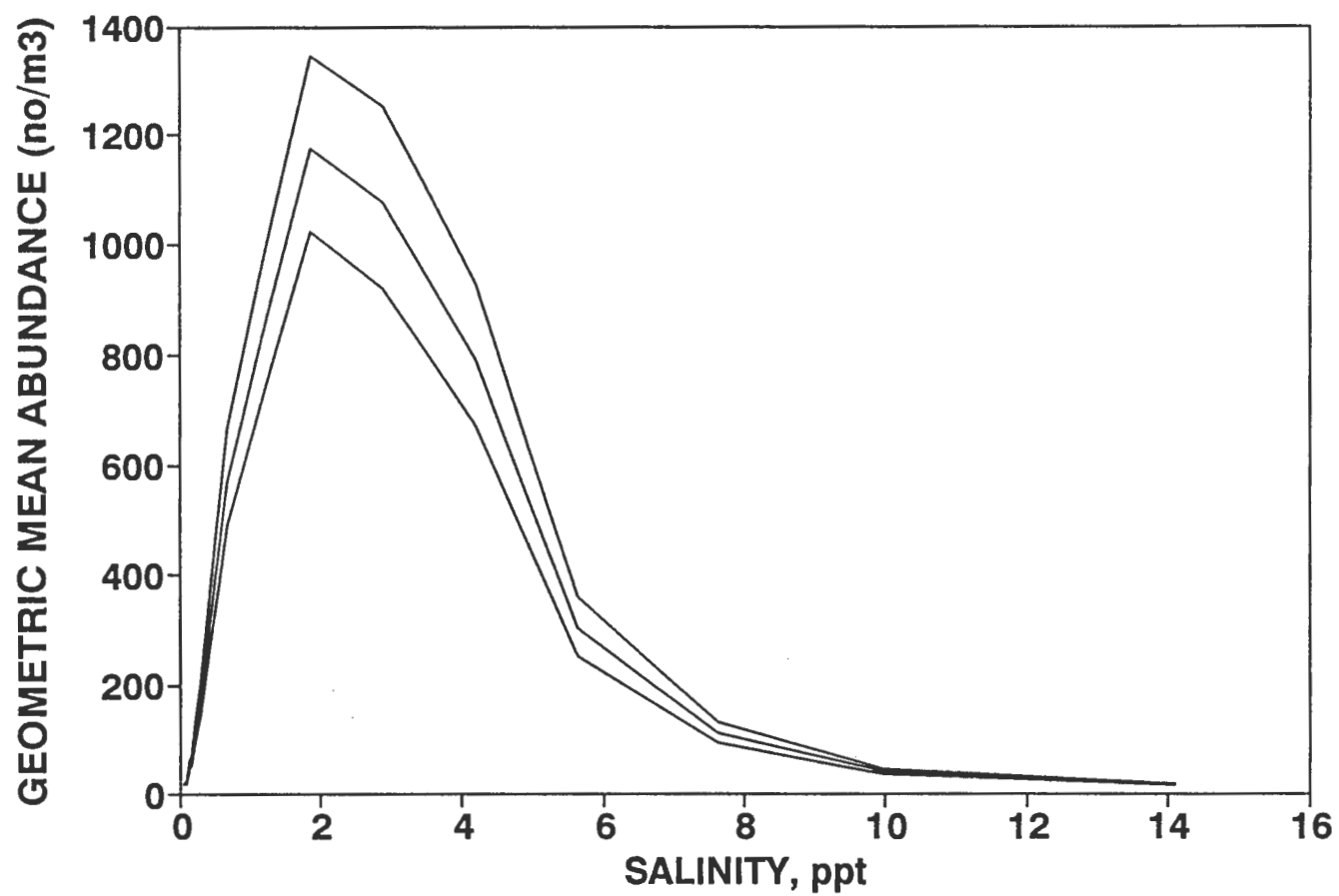
Figure 33. *Eurytemora affinis.* Geometric mean abundance and 95% confidence intervals converted to antilogs (upper and lower lines), by salinity.
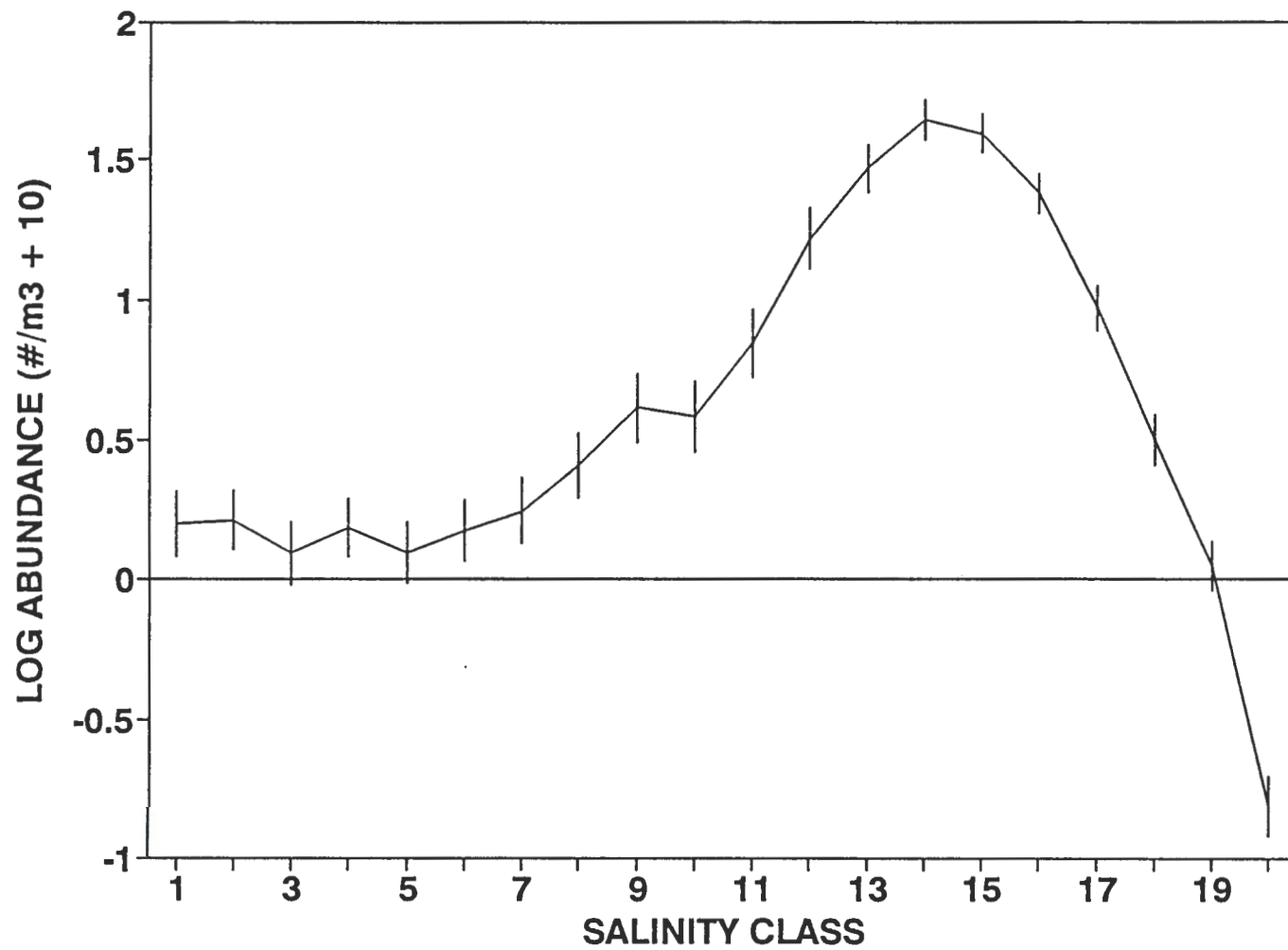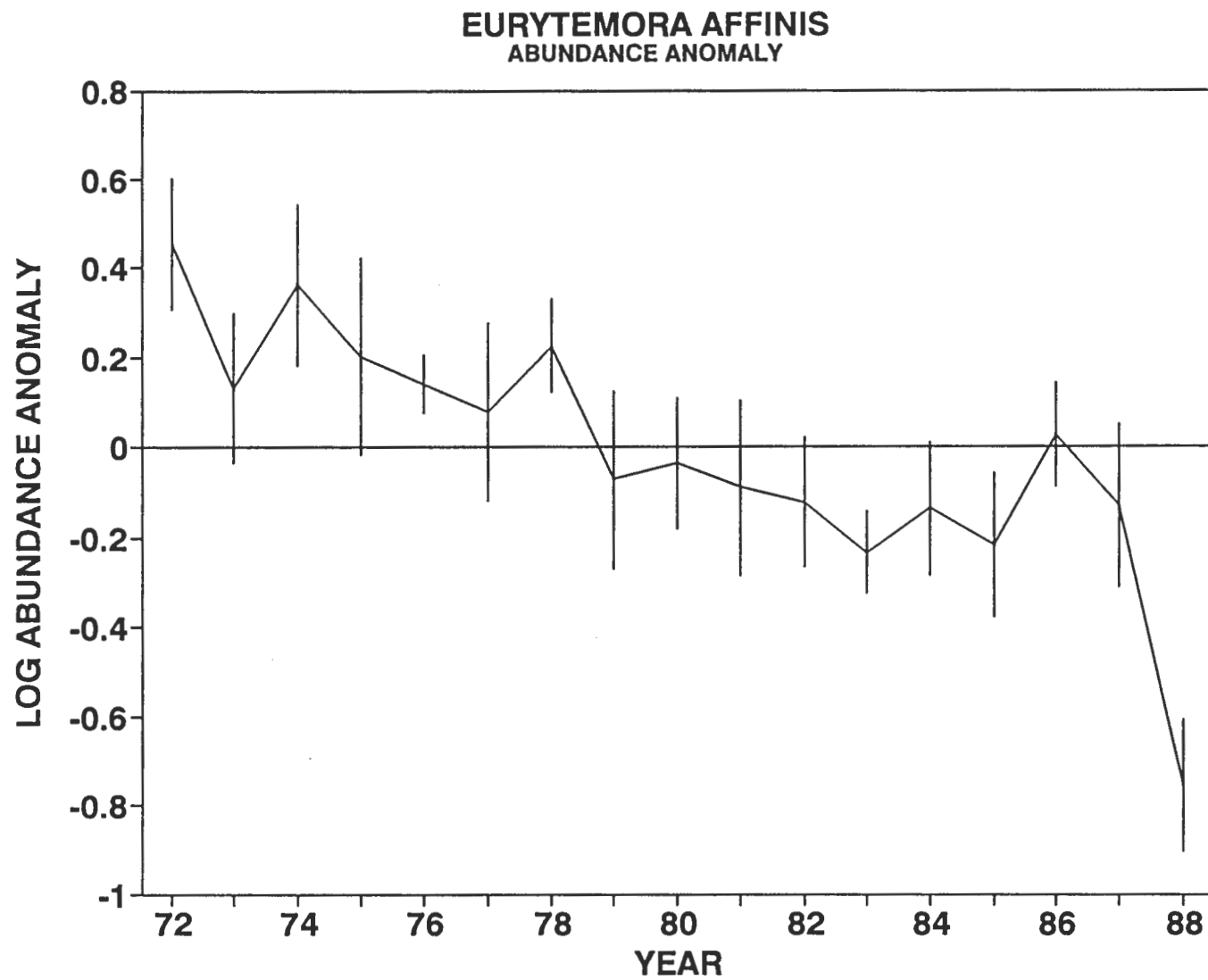
Figure 34. *Neomysis mercedis*. Mean and 95% confidence intervals by salinity class.

Figure 35. *Neomysis mercedis.* Geometric mean abundance and 95% confidence intervals converted to antilogs (upper and lower lines), by salinity.

EURYTEMORA AFFINIS
ABUNDANCE ANOMALY

Figure 36. *Eurytemora affinis* abundance anomalies. Annual means and 95% confidence intervals.
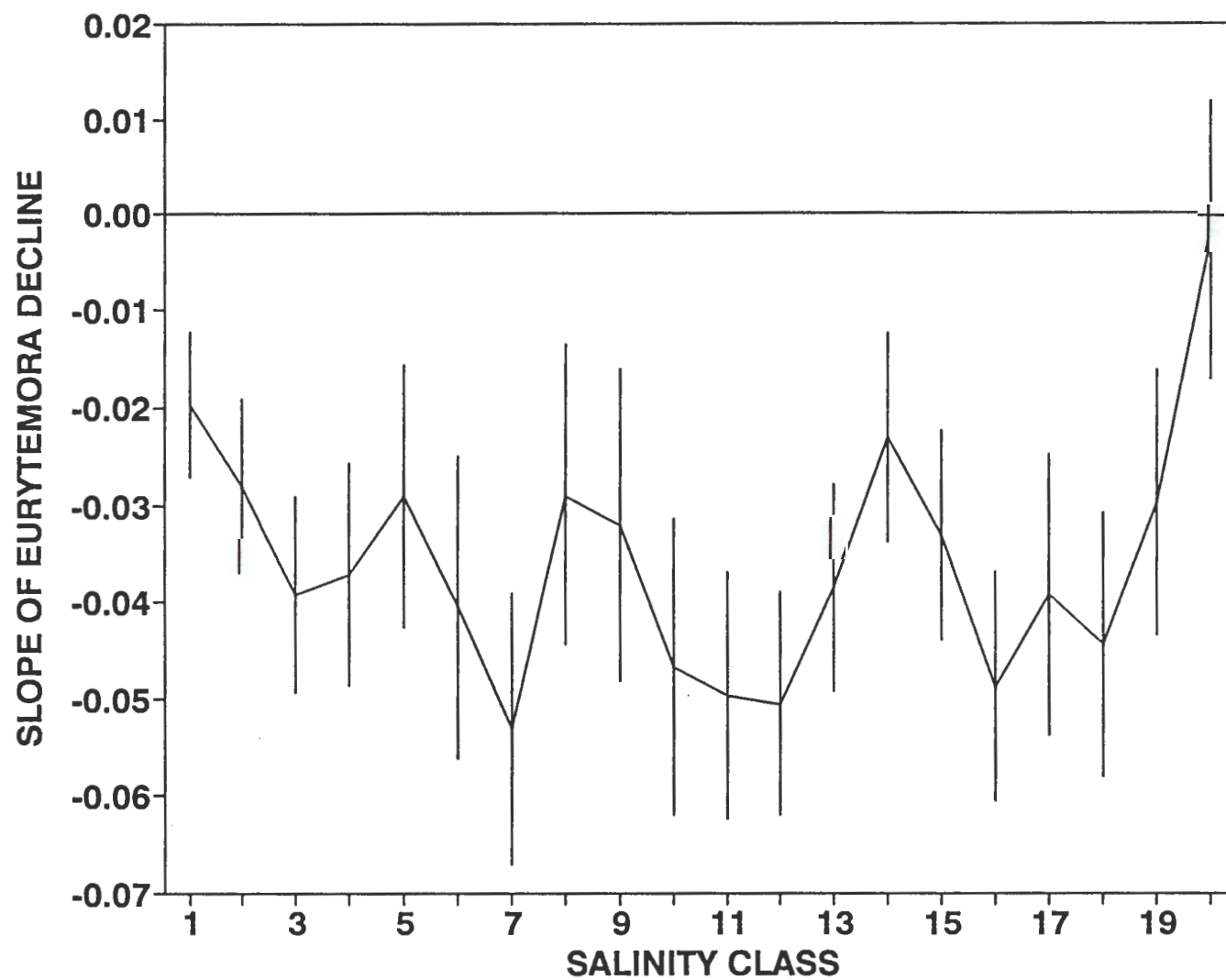
Figure 37. *Eurytemora affinis*. Slopes of linear regression of log abundance vs. year, means and 95% confidence limits by salinity class.
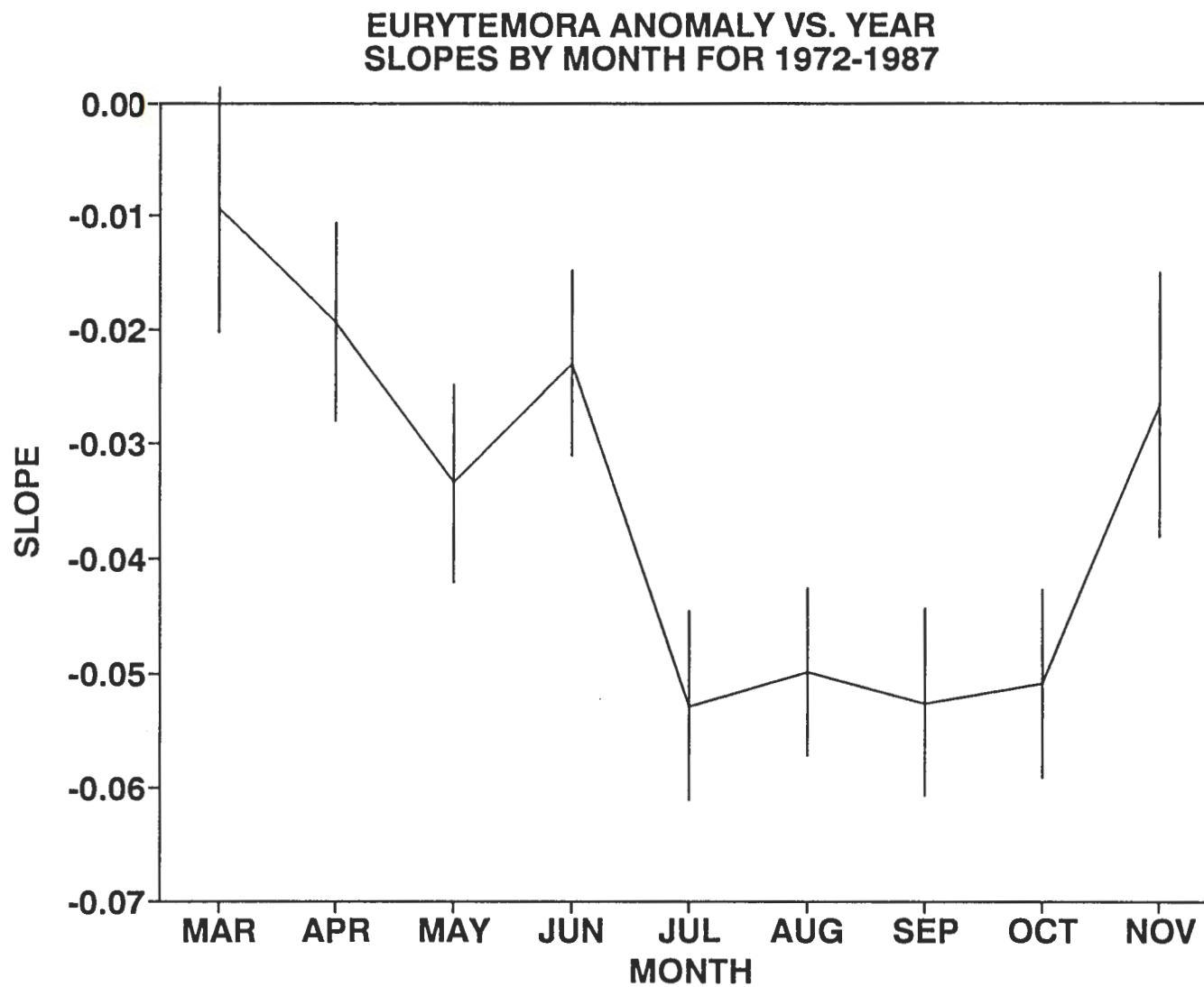
Figure 38. *Eurytemora affinis*. Slopes of linear regression of log abundance vs. year, means and 95% confidence limits by month.
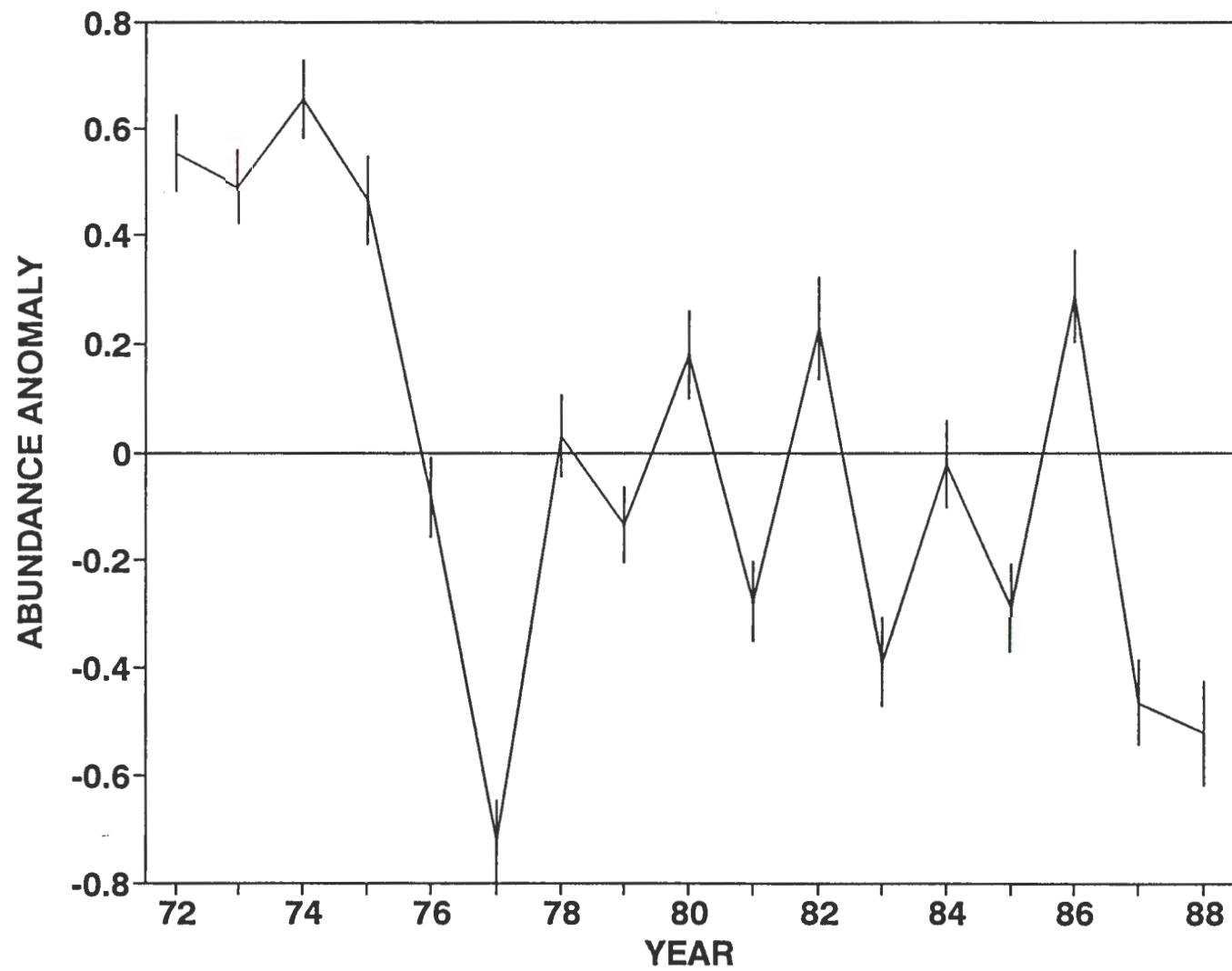
Figure 39. *Neomysis mercedis* abundance anomalies. Annual means and 95% confidence intervals.

EURYTEMORA ABUNDANCE
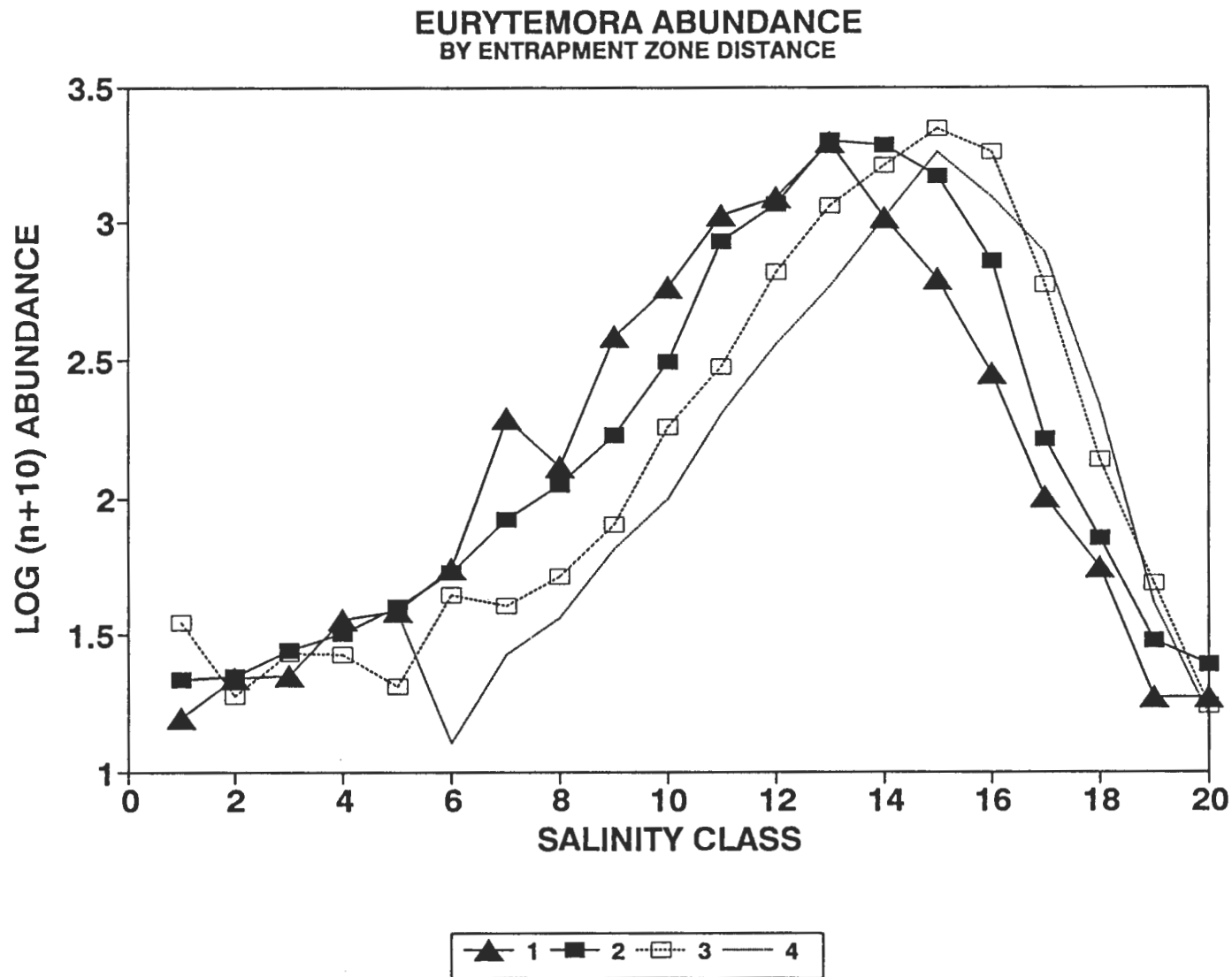BY ENTRAPMENT ZONE DISTANCE

Figure 40. *Eurytemora affinis*. Abundance vs. salinity class for 4 categories of entrapment zone position determined as distance from the Golden Gate Bridge.
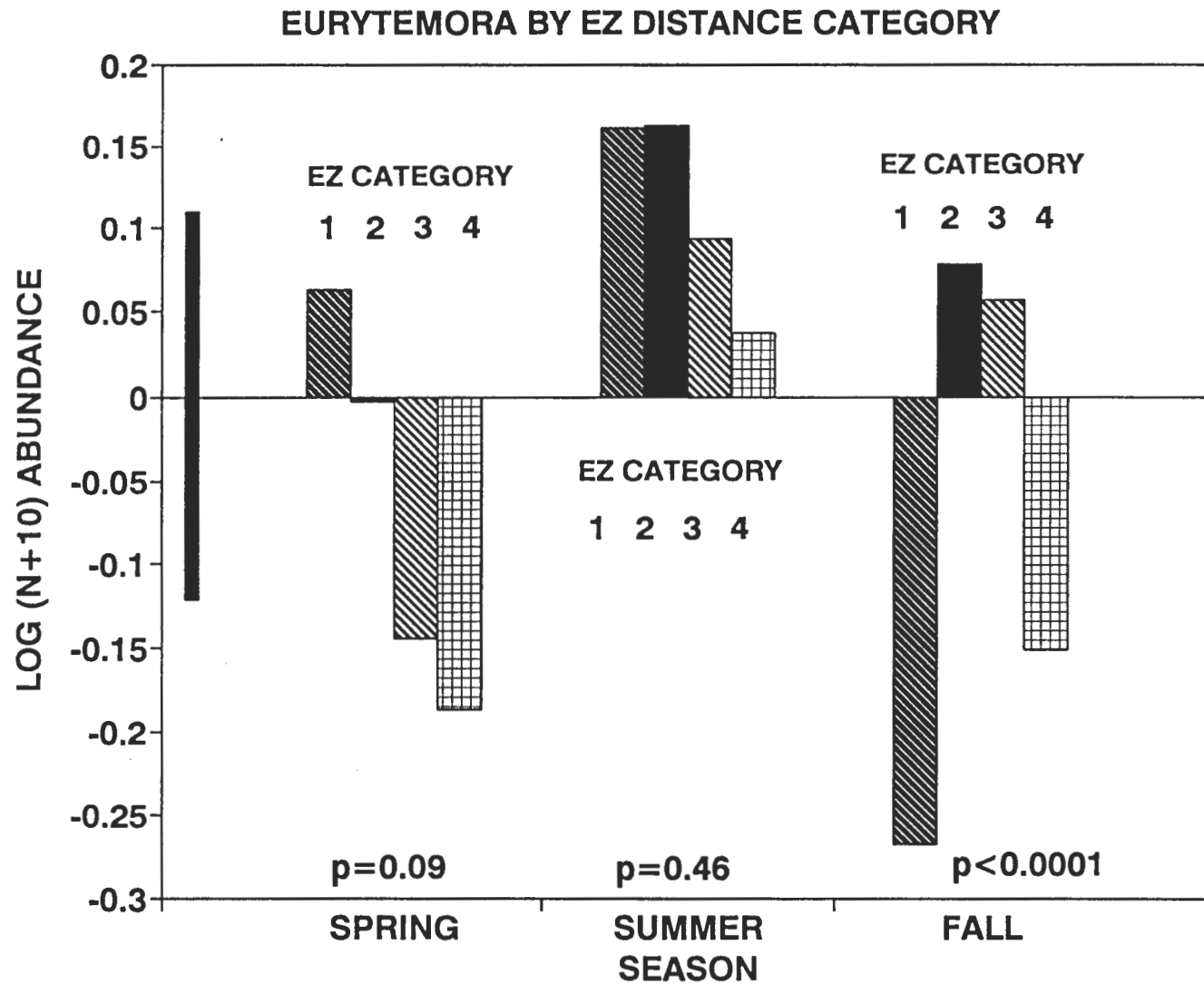
EURYTEMORA BY EZ DISTANCE CATEGORY

Figure 41. *Eurytemora affinis.* Abundance anomaly (Salinity class, month, and annual trend removed) for 4 categories of entrapment zone position, by season. Each value is the grand mean of values from the 5 contiguous salinity classes having the highest values of abundance. Vertical bar at left is the 95% confidence limit for a single value. ANOVA p values are given at bottom.
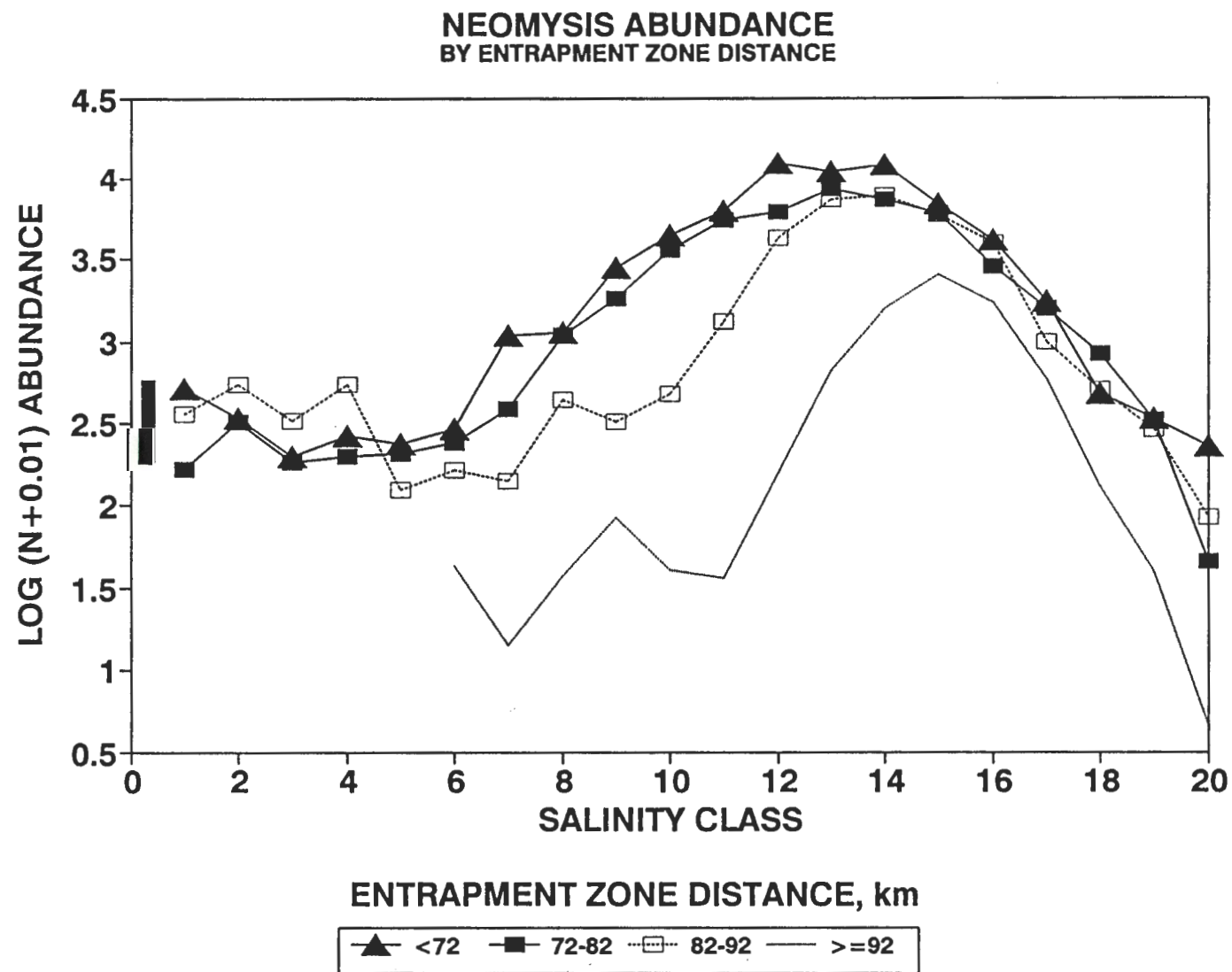
NEOMYSIS ABUNDANCE
BY ENTRAPMENT ZONE DISTANCE

ENTRAPMENT ZONE DISTANCE, km

| ▲ <72 | ■ 72-82 | ⊡ 82-92 | —— >=92 |

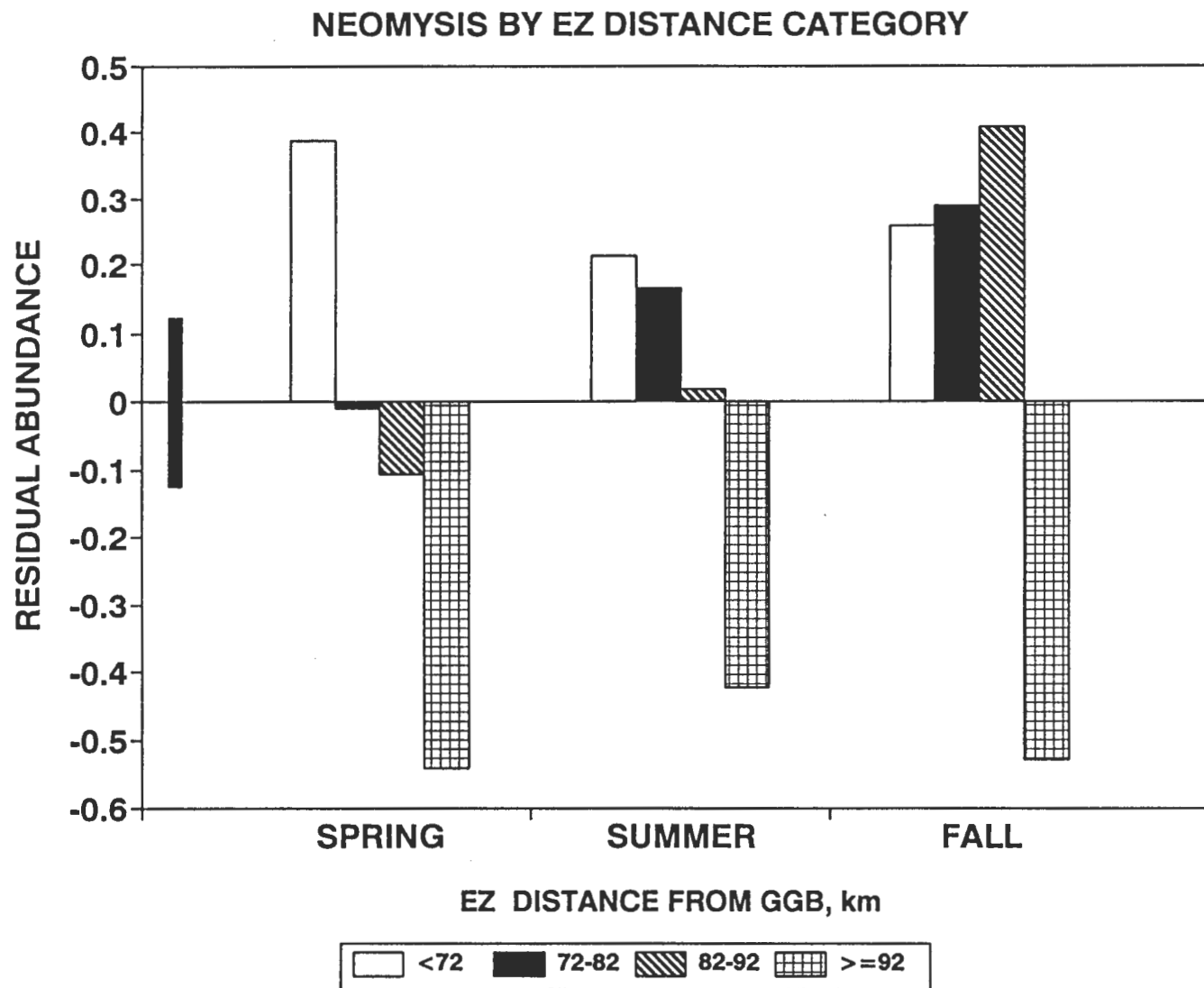**Figure 42.** *Neomysis mercedis.* As in Figure 39.

Figure 43. *Neomysis mercedis.* As in Figure 41, except that temperature relationship has been removed.
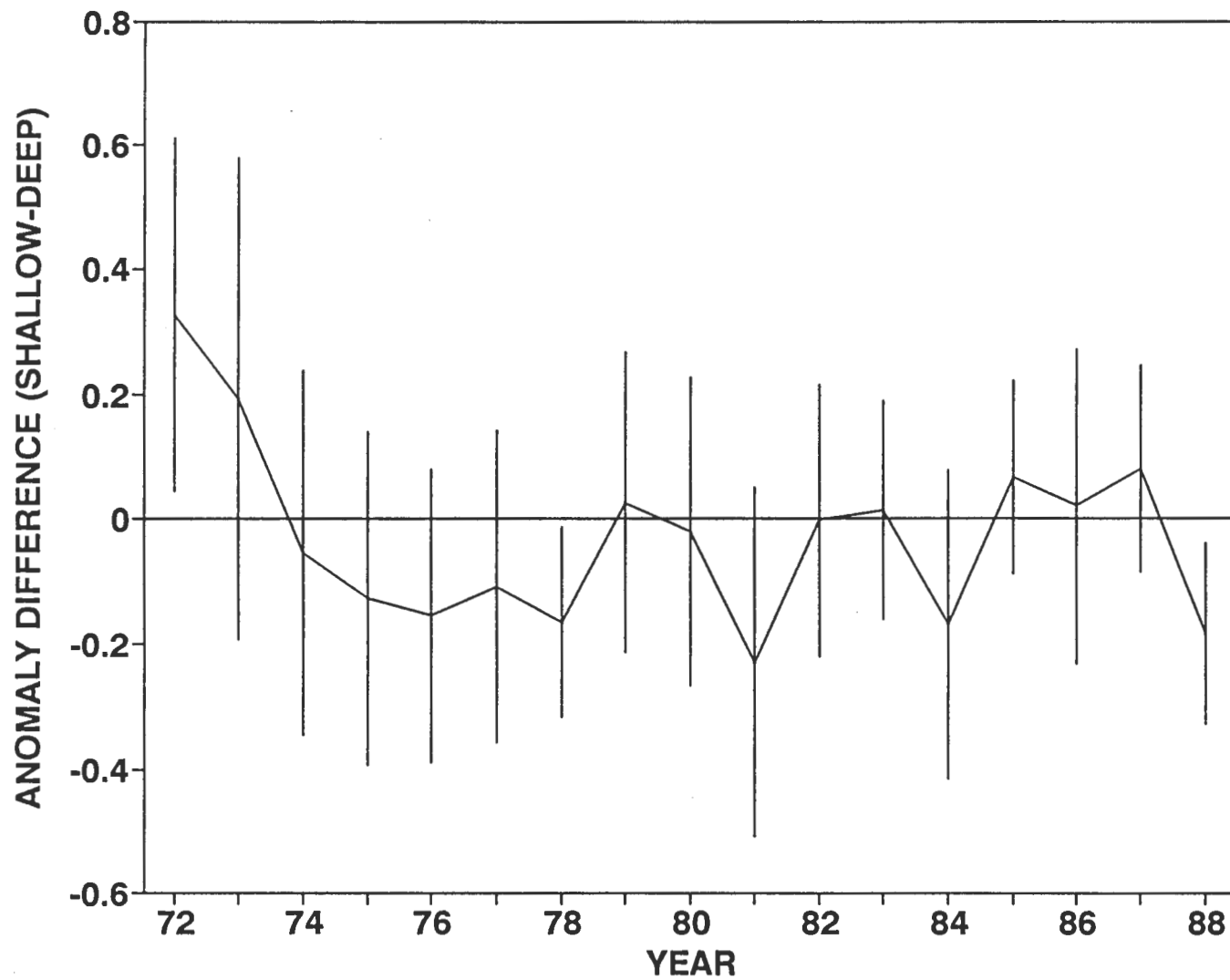
Figure 44. *Eurytemora affinis.* Difference in abundance anomaly between two shallow stations (28 and 40) in Grizzly and Honker Bays and nearby deep stations. Annual means and 95% confidence limits for monthly differences.
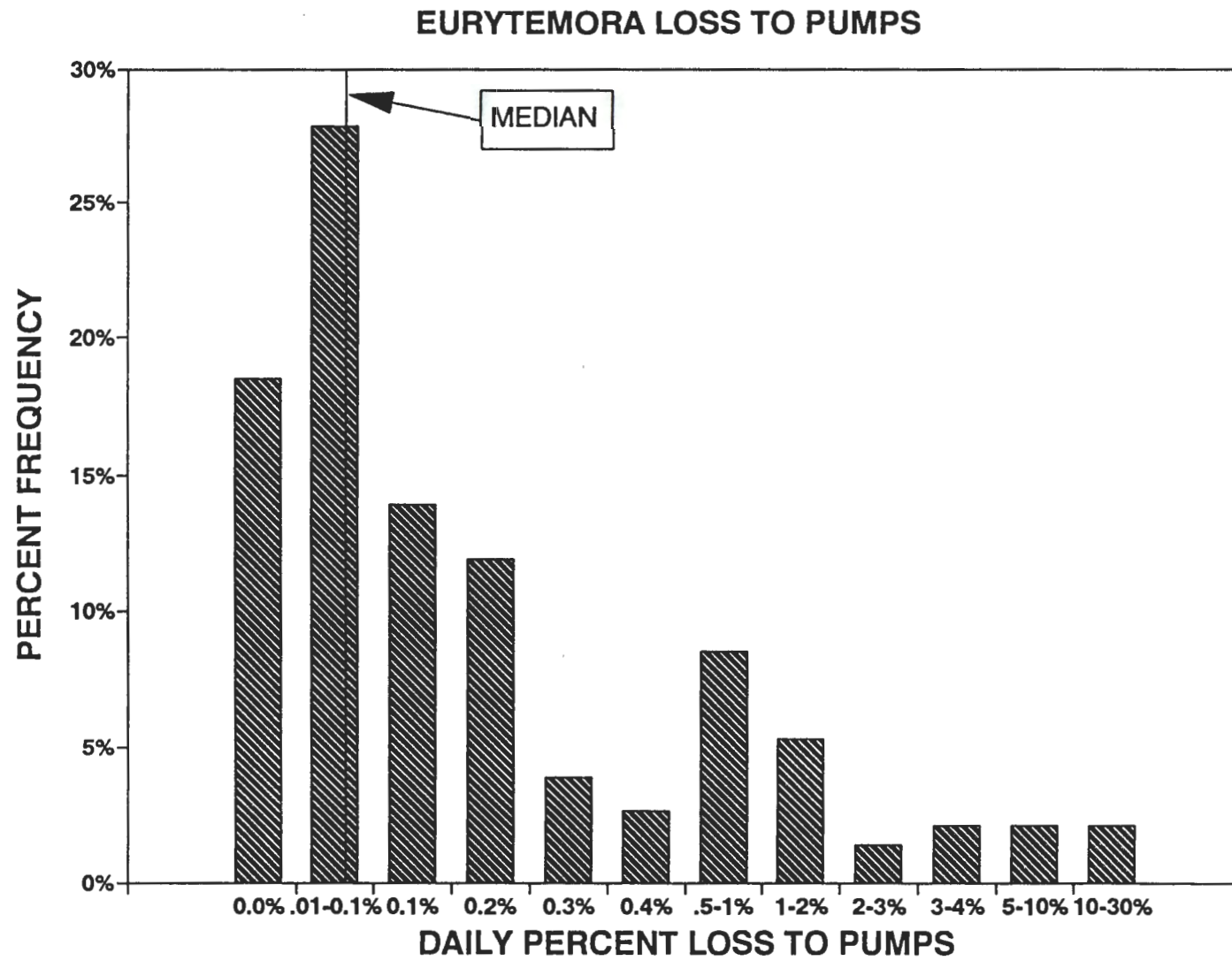
Figure 45. *Eurytemora affinis.* Frequency distribution of estimated proportion of the population lost to export pumps.
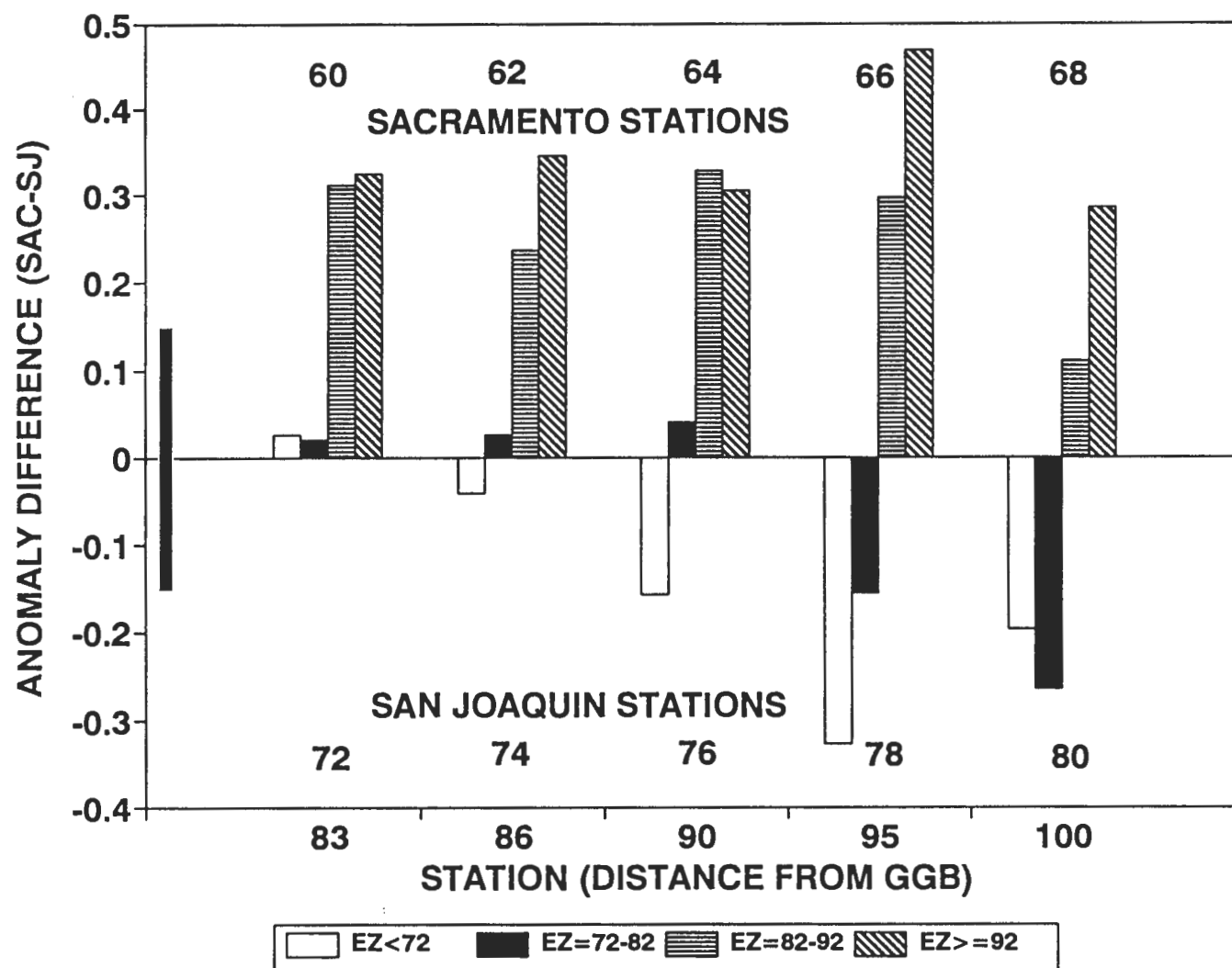
Figure 46. *Eurytemora affinis.* Differences in abundance anomalies between Sacramento and San Joaquin River stations matched for distance up the estuary, for each of 4 positions of the EZ. Distances are given at the bottom and station numbers within the box.
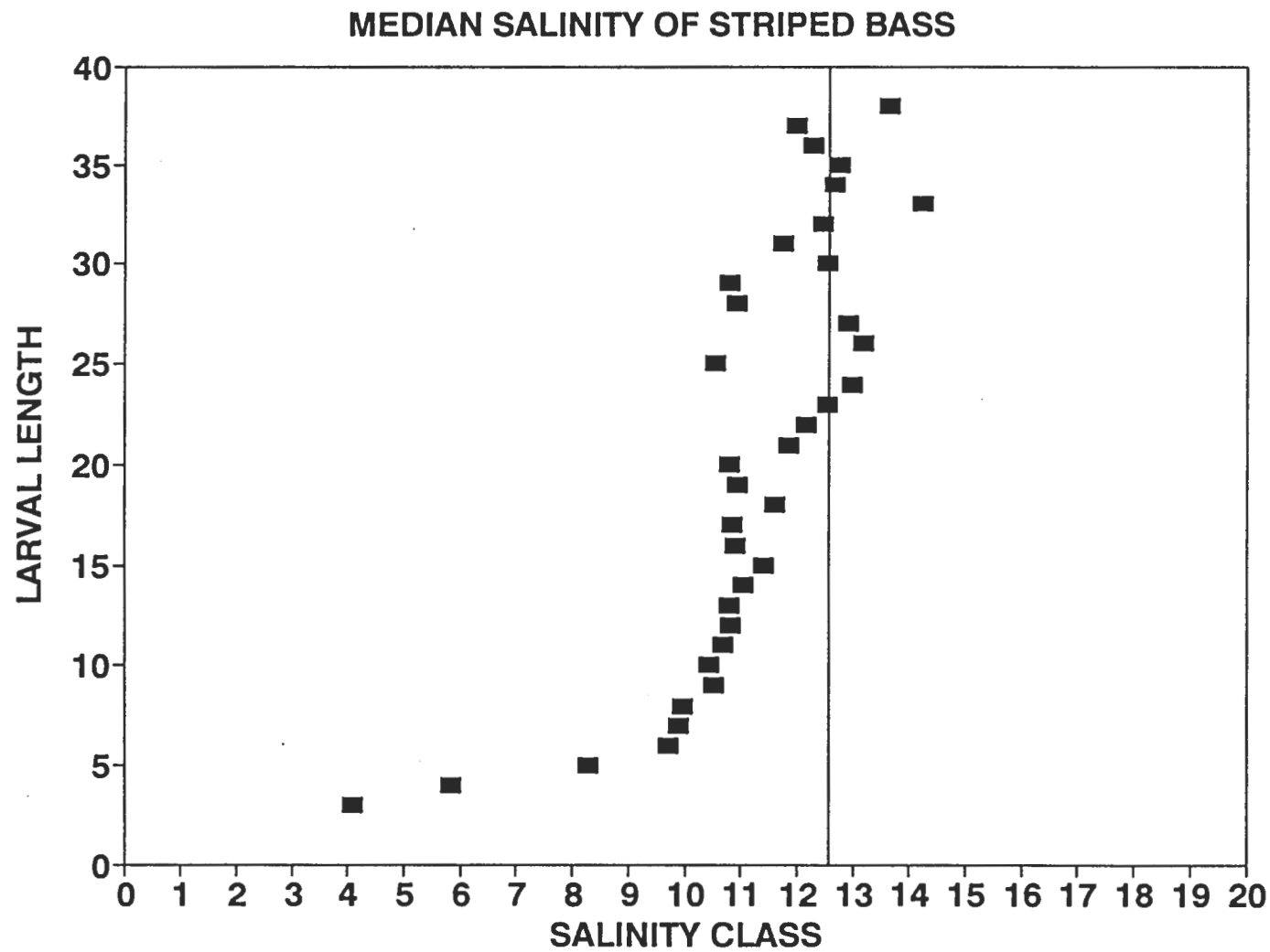
Figure 47. Median position in terms of salinity of striped bass larvae vs. larval length.
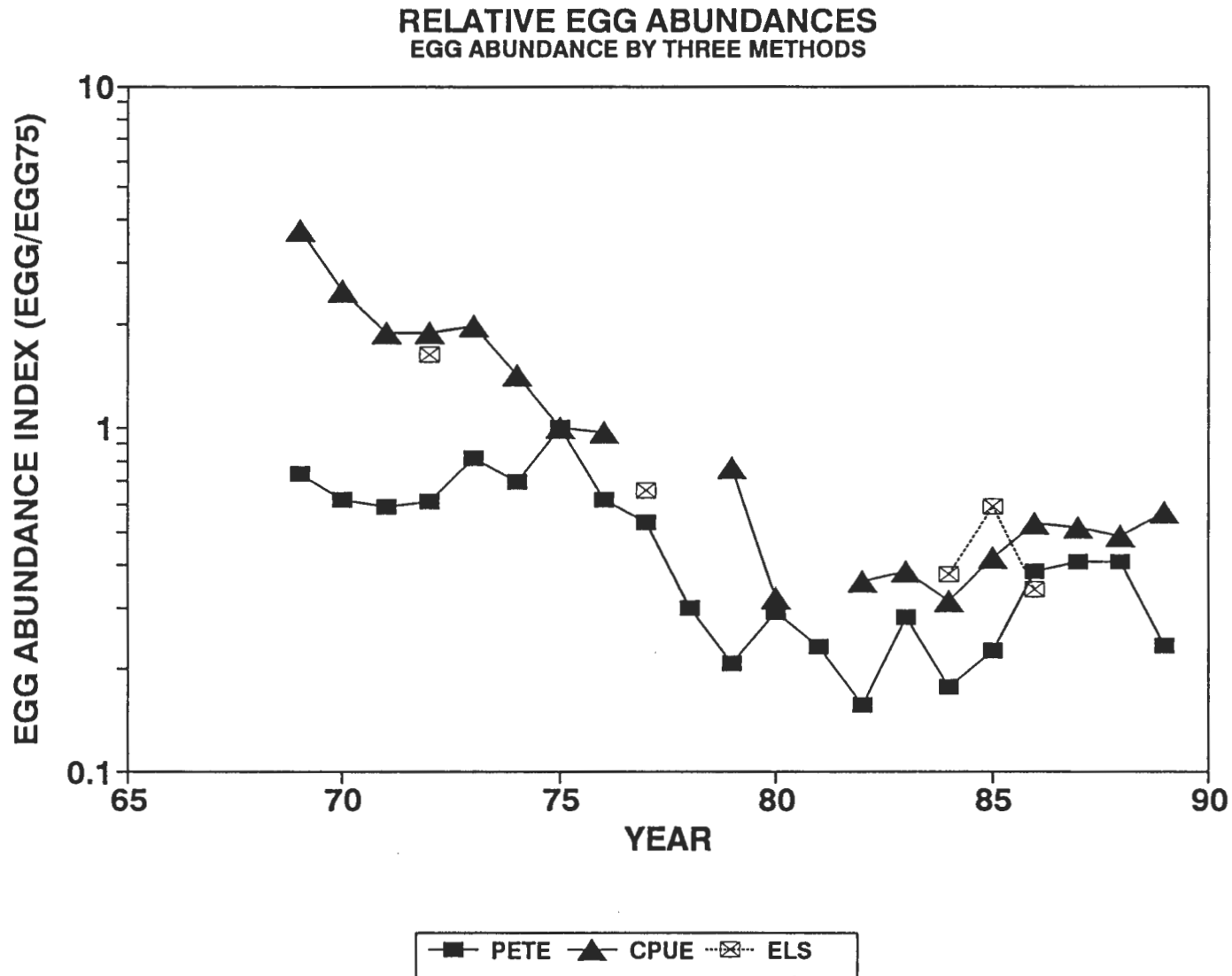
Figure 48. Time trend of three egg abundance indices: Peterson abundance (PETE), Catch per effort index (CPUE), and egg and larval survey index (ELS). All values have been scaled to make the 1975 values the same, then log transformed.

LOG RELATIVE SURVIVALS TO YOY
BASED ON EGG ABUNDANCE BY THREE METHODS

Legend: PETE, CPUE, ELS
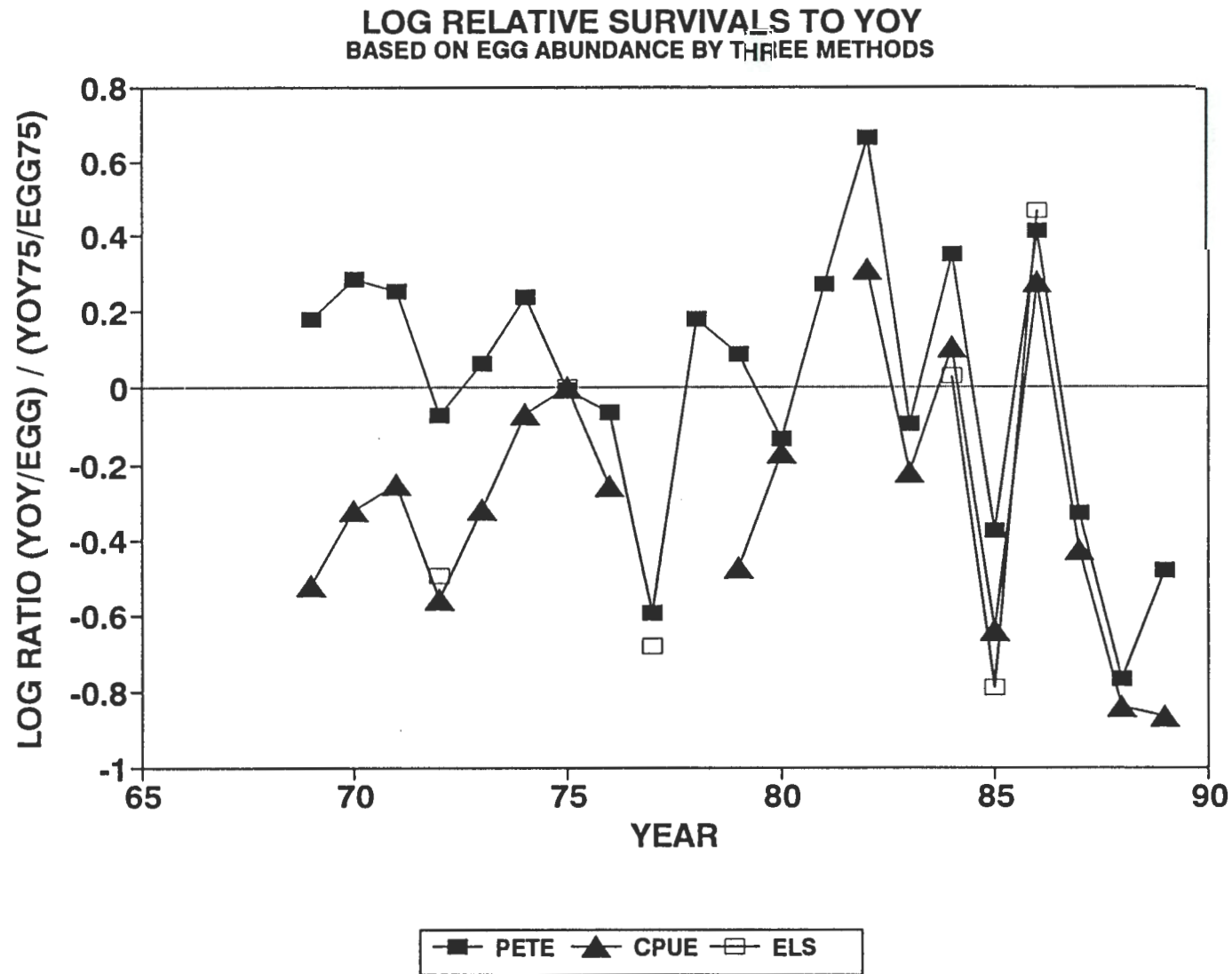
Figure 49. As in Figure 48 for relative survival of eggs to young of the year. Each value is calculated as the ratio of YOY index to egg index, scaled by the 1975 value, and log transformed.

LOG RELATIVE SURVIVALS TO YOY
BASED ON EGG ABUNDANCE BY THREE METHODS

Figure 50. Relative survival by the three indices vs. EZ position.

Life History and Status of Delta Smelt

in the Sacramento-San Joaquin Estuary, California

Peter B. Moyle and Bruce Herbold

Department of Wildlife and Fisheries Biology

University of California, Davis

Davis, California 95616 USA

and

Donald E. Stevens and Lee W. Miller

California Department of Fish and Game

4001 N. Wilson Way

Stockton, California 95205 USA

Abstract.--The delta smelt (Osmeridae: Hypomesus transpacificus McAllister) is endemic to the upper Sacramento-San Joaquin estuary. It is cl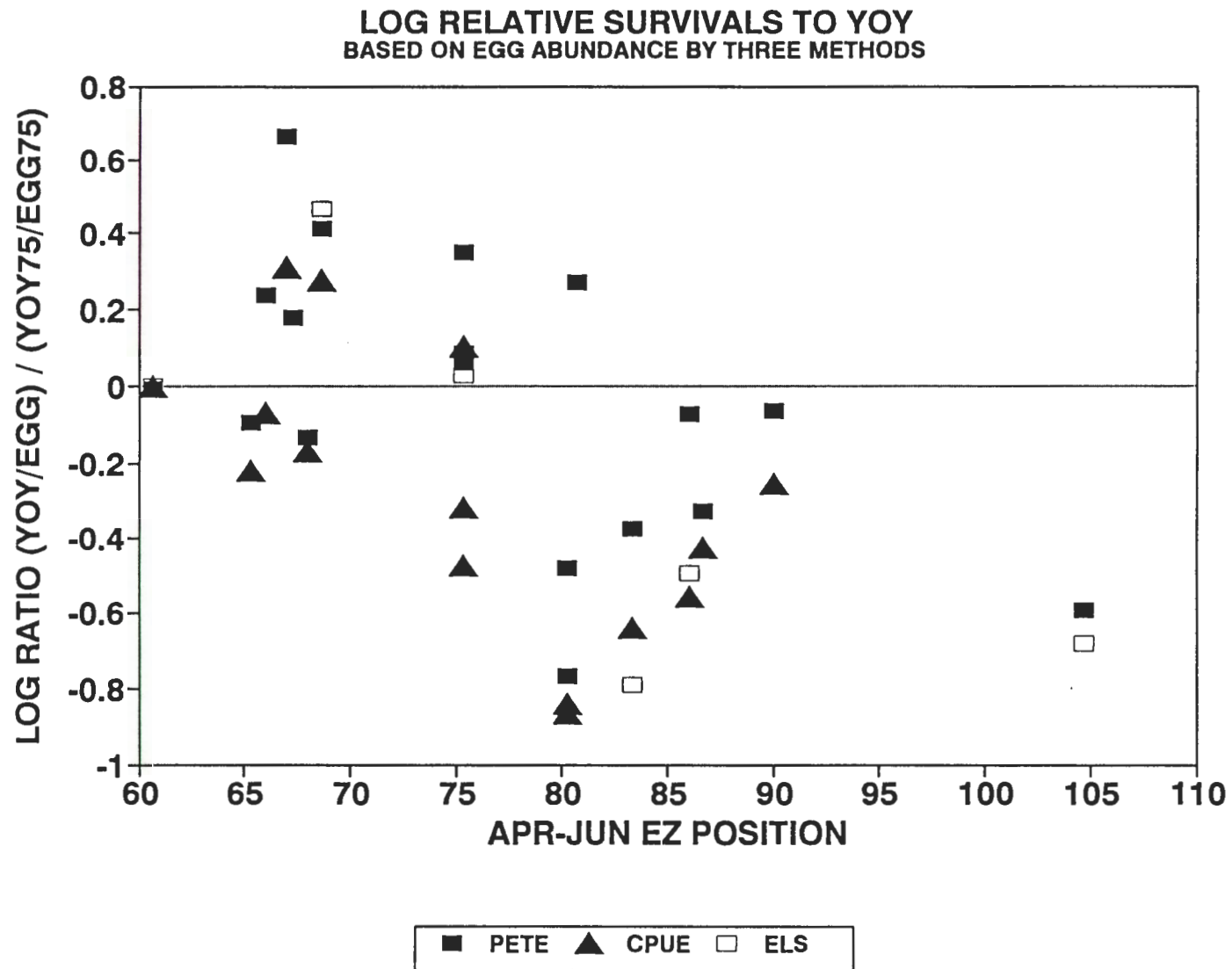osely associated with the freshwater-saltwater mixing zone except when it spawns in fresh water, primarily during March, April, and May. The delta smelt feeds on zooplankton, principally copepods. In 1972-74, its dominant prey item was the native copepod Eurytemora affinis, but in 1988 it was the exotic copepod Pseudodiaptomus forbesi. Because the delta smelt basically has a one-year life cycle and low fecundity (= 1907 eggs), it is particularly sensitive to changes in estuarine conditions. Townet and midwater trawl samples taken throughout the delta smelt's range from 1959 through 1981 showed wide year-to-year fluctuations in population densities. Surveys encompassing different areas show declines in different years between 1980 and 1983. After 1983, however, all studies show that the populations remained at very low densities throughout most of their range. The recent decline of delta smelt coincides with an increase in the diversion of inflowing water during a period of extended drought which has restricted the mixing zone to a relatively small area of deep river channels and, presumably, increased the entrainment of smelt. Changes in food supply, invasions by exotic species, and presence of toxic compounds are also associated with the decline. Restoration of the delta smelt to a sustainable population size is likely to require maintenance of the mixing zone in Suisun Bay and maintenance of net seaward flows in the lower San Joaquin River during the period when larvae are present. Improving conditions for delta smelt should also improve conditions for other fishes with planktonic larvae that have shown severe declines in recent years.

The delta smelt (Hypomesus transpacificus) is a small fish endemic to the upper Sacramento-San Joaquin estuary in central California (McAllister 1963; Moyle 1976; Wang 1986). The smelt has declined in abundance in recent years and its ability to persist in the estuary is in doubt because of major environmental changes that have taken place, including increased diversion of freshwater inflow for irrigated agriculture and urban use (Nichols et al. 1986; Williams et al. 1989; Moyle et al. 1989). Reduced freshwater outflow is correlated with poor year classes in striped bass (Morone saxatilis), chinook salmon (Oncorhynchus tshawytscha), American shad (Alosa sapidissima), longfin smelt (Spirinchus thaleichthys), and splittail (Pogonichthys macrolepidotus), presumably because of decreased survival of larval and juvenile fish (Turner and Chadwick 1972, Stevens 1977a, Kjelson et al. 1982; Daniels and Moyle 1983, Stevens and Miller 1983; Stevens et al. 1985). Since the late 1970s, there has been a decline of most fishes with pelagic larvae in the upper estuary, including delta smelt (Moyle et al. 1985; Herbold and Moyle, unpublished data). Stevens and Miller (1983), however, could not find any relationship between delta smelt abundance and outflow.

We present the following information on delta smelt: (1) a summary of known aspects of its life history; (2) diet, especially in relation to the recent invasion of several exotic species of zooplankton (Orsi et al. 1983; Ferrari and Orsi 1984); (3) fecundity; (4) population trends since 1959; (5) distribution patterns since 1980; and (6) factors affecting abundance. This information supports the proposed listing of delta smelt as a threatened or endangered species.

Life History

Delta smelt are confined to the upper Sacramento-San Joaquin estuary (Figure 1). Historically, the upstream limits of their range have been around Sacramento on the Sacramento River and Mossdale on the San Joaquin River, with the lower limit being Suisun Bay (Radtke 1966; Moyle 1976). During times of exceptionally high outflow from the rivers, they may be washed into San Pablo Bay but they do not establish permanent populations there (Ganssle 1966). Delta smelt inhabit surface and shoal waters of the main river channels and Suisun Bay where they feed on zooplankton (this study). Their distribution within the estuary shifts from year to year depending on outflow.

Captures of larval delta smelt indicate that spawning can take place in fresh water any time from late February through May, when water temperatures range from 7 to 15°C (Wang 1986). Spawning occurs in shallow water along the edges of the rivers and adjoining sloughs (Radtke 1966; Wang 1986) but spawning behavior has not been observed. Delta smelt embryos are demersal and adhesive, sticking to substrates such as rocks, gravel, tree roots, and emergent vegetation (Moyle 1976, Wang 1986). Hatching occurs in 12-14 days, assuming development rates of the embryos are similar to those of the closely related wagasaki, H. nipponensis (Wales 1962).

After hatching, the buoyant larvae are carried by currents downstream into the mixing zone of the estuary where incoming saltwater mixes with outflowing fresh water (Peterson et al. 1975; other synonyms or related terms for this region include null zone, entrapment zone and zone of maximum turbidity). The mixing currents keep the larvae circulating with the abundant zooplankton that also occur in this zone (Orsi and Knutson 1979; Siegfried et al. 1979; Stevens et al. 1985). Growth is rapid and the juvenile fish are 40-50 mm fork length (FL) by early August (Erkkila et al. 1950; Ganssle 1966; Radtke 1966). Delta smelt become mature when 55 to 70 mm FL and rarely grow larger than 80 mm FL. The largest delta smelt on record is 126 mm FL (Stevens et al. 1990). Delta smelt larger than 50 mm FL become increasingly rare in samples in March through June, indicating that the vast majority of adults die after spawning, completing their life cycle in one year (Erkkila et al. 1950; Radtke 1966; unpublished data, CFG and UCD).

Methods

Sampling. Only two smelt species commonly occur in the Sacramento-San Joaquin Estuary, delta smelt and longfin smelt; once past the larval stages, they are easily distinguished on the basis of color, smell, and gross anatomy (Moyle 1976; Wang 1986). Delta smelt were collected in four independent surveys: (1) a summer townet survey of the California Department of Fish and Game (CFG), (2) an autumn midwater trawl survey in the upper estuary by CFG, (3) a monthly midwater trawl survey in the lower estuary by CDFG (bay survey), and (4) a monthly otter trawl survey of Suisun Marsh by the University of California, Davis (UCD). In all surveys, fish captured were identified, measured (FL in CFG studies, SL in UCD study), and either returned to the water or preserved for dietary analysis.

The summer townet survey samples the Delta and Suisun Bay during June and July, to determine the abundance of young striped bass (Turner and Chadwick 1972). The sampling gear and methods are described in detail in Turner and Chadwick (1972) and Stevens (1977b). This sampling program began in 1959 and has been conducted in all subsequent summers except 1966, although no records were kept of smelt numbers in 1967 and 1968. On each survey, three tows are made at each of 30 sites; two to five surveys are made each year at two week intervals. To standardize efforts among years, for this study we only used the data from the first two surveys of each year. Annual abundance indices for delta smelt were calculated by summing, over all sample sites, the products of total catch in all tows at a site and the water volume at the site in acre feet (Chadwick 1964). The index for each year is the mean of the indices for the two surveys, divided by 1000. Except during wet years (when the smelt are washed into San Pablo Bay), this survey covers the nursery areas of delta smelt, so should provide a good indication of abundance in early summer.

The autumn midwater trawl survey is conducted using a trawl 17.6 m long with a mouth opening of 3.7 m2, described by Von Geldern (1972). The trawl was dragged at about 70 cm/s and was most effective in catching fish <10 cm long. Collecting stations were established in standardized locations scattered from San Pablo Bay through Suisun Bay and the Delta, upstream to Rio Vista on the Sacramento River and Stockton on the San Joaquin River. Each month, unless prevented by severe weather or malfunctioning equipment, 87 stations were each sampled with one 12-minute, depth-integrated tow. Surveys were conducted during September, October, November, and December from 1967 through 1989, except in 1974 and 1979, in November 1969, and in September and December 1976. Monthly abundance indices for delta smelt were calculated by summing, over 17 subareas of the estuary, the product of the mean catch per trawl in each subarea times the water volume in each subarea. The annual abundance index is the sum of the four monthly indices; abundance indices for

months not surveyed in 1969 and 1976 were extrapolated from the months actually sampled.

The bay survey is a monthly trawling program that began in 1980 (Armor and Herrgeseli 1985). The 42 stations of the bay survey are distributed throughout the lower estuary from South San Francisco Bay upstream to the confluence of the Sacramento and San Joaquin Rivers. To permit comparisons of catches across years, we restricted our analysis of the bay survey data to the 19 stations sampled in all years within the range of delta smelt. The bay study uses both midwater trawls and otter trawls and, since 1981, has recorded salinity and temperature profiles of each sampling site.

The Suisun Marsh survey conducted by UCD has been a monthly sampling program using an otter trawl (2 x 5.3 m opening) to sample the fish populations in Suisun Marsh since 1979 (Moyle et al. 1985). Two five or ten minute tows are made at 10 consistent locations. Because the sloughs of the marsh are relatively shallow (2-3 m), the otter trawl samples most of the water column and is most effective in catching fish <10 cm SL. Suisun Marsh is a tidal marsh adjacent to Suisun Bay.

To summarize: the summer townet survey and the autumn midwater trawl survey provide long-term abundance data and encompass most of the historic range of delta smelt, but they are available for only part of each year. The bay survey encompasses all months of the year but is limited to the western half of the delta smelt's historic range and began in 1980; the Suisun Marsh study samples year-round in habitat types not sampled by other studies but is limited to a much smaller geographic area and began in 1979.

Feeding habits. Diet was determined by examining the stomachs of (1) adult smelt captured between September 1972 and July 1974 when midwater trawl surveys were conducted nearly every month, (2) postlarval smelt collected in May, 1977, and (3) adult smelt captured in surveys of November and December, 1988. Each fish was measured (standard length, SL) and its stomach contents examined. All organisms were identified, counted, and their relative volume determined using the points system of Hynes (1950). When the 1972-1974 stomachs were examined (in 1974), copepods were not identified to species. However, examination in 1989 of the stomachs of 45 additional smelt from the same samples indicated that the only copepod present was Eurytemora affinis.

Fecundity. Fecundity was determined from the ovaries removed from 24 females collected in mid-January and early March, 1973. Ovaries from each female were placed on a petri dish and air-dried until eggs were hard and could be easily separated from other tissue. Once the ovarian tissue was removed, eggs were weighed to 0.01 mg. Subsamples of eggs were then removed, weighed, and counted until at least 20% (by weight) of the eggs had been counted. Total number of eggs was calculated using the number/weight proportion determined from the subsamples. All the eggs were counted from four ovaries and the fecundity compared to that determined from subsamples; this comparison indicated that the subsample method overestimated fecundity by about 15%. Two means were calculated: the uncorrected mean was the based on the actual estimates and the corrected mean was based on the estimates plus 15% to account for the bias identified from the total counts of four ovaries.

Abundance trends. Abundance data for the four surveys were summarized in several ways to permit comparison of various data sets. For the Bay study and UCD study which had year-round sampling at consistent study sites, summaries were (1) number of smelt per trawl for each month , (2) presence or absence of smelt in trawls for each month , (3) mean number of smelt caught per trawl in the trawls with delta smelt for each month, and (4) total smelt caught per trawl for each year. Indices of abundance were calculated based number of fish caught and the volume of water sampled at each area sampled for the summer townet survey and the autumn midwater trawl survey (Stevens and Miller 1983; Armor and Herrgesell 1985). These indices reduce the potential bias associated with geographic variations in delta smelt distribution relative to the uneven spatial distribution of sampling sites. The results of the various analyses were similar, so those which showed trends most clearly were used.

Environmental factors. Four major factors were examined in relation to smelt distribution and abundance: salinity (measured as conductivity in CFG studies), temperature, depth, and freshwater

outflow. At each sampling station in the Bay and UCD studies and at many of the sampling stations of the summer and autumn surveys, conductivity and/or salinity, and temperature were measured at the surface by various means. Some conductivity measurements were also made with a conductivity bridge in the laboratory, from water samples collected in the field. To determine the location of the mixing zone, we used conductivity data collected monthly since January 1981 by the Bay Study, in which both surface and bottom conditions were measured by mounting the probe on a weighted support and dropping it to the bottom and retrieving it to the surface. Values of salinity were calculated from the measured conductivities and temperatures. Large differences in salinity between the surface and bottom indicated the presence of stratification, as incoming fresh water is less dense than tidal salt water. A small salinity difference indicated a well-mixed water column or stations located entirely in fresh water.

A single depth measurement (m) at mean low water was used to characterize each study site for the length of the study, although factors such as tide and outflow resulted in depths at each site varying as much as one meter among sampling times.

Data used to examine monthly amounts and patterns of freshwater outflow were obtained from the DAYFLOW program of the California Department of Water Resources (DWR). This program estimates, from various measurements made by DWR, a number of variables related to the amount of fresh water flowing through the estuary, including net delta outflow, the proportion of water being diverted, and the amount and direction of flow in the lower San Joaquin River (DWR 1986).

Results

Feeding Habits

Postlarval delta smelt (mean SL 15 mm, n=24) fed exclusively on copepods; the stomachs of the 1977 fish contained 68% Eurytemora affinis, 31% Cyclops sp., and 1% harpactacoid copepods. Adults fed largely on copepods at all times of the year, although cladocerans were seasonally important, with opossum shrimp, Neomysis mercedis, usually of secondary importance (Table 1). In the 1972-1974 samples, the principal copepod species eaten was Eurytemora affinis, but in the 1988 samples the dominant copepod was the introduced species Pseudodiaptomus forbesi. A few Sinocalanus doerrii, another exotic species, were also eaten in 1988.

Fecundity

Mean corrected fecundity for delta smelt (n=24) was 1907 eggs, with a range of 1247 to 2590 (uncorrected mean was 2191, with a range of 1433 to 2975). Lengths of fish examined were from 59 to 70 mm SL. There was no relationship between length and fecundity. All eggs were about the same size, so each fish probably spawned over a fairly short period of time.

Abundance Trends

In the two long-term studies, catches of delta smelt varied widely across years (Figure 2). In the summer townet survey, the peak index of 62.5 in 1978 was 78 times greater than the lowest index of 0.8 in 1985. Prior to 1980, the index usually fluctuated between 10 and 40. After 1980, the index declined and has remained below 10 since 1982. While similar low indices occurred in 1963, 1965, and 1969, they did not occur in consecutive years. In the autumn midwater trawl survey, the highest index was 578 (in 1970), which was 15 times greater that the lowest index of 109 (in 1985). Until 1980, the index usually fluctuated between 400 and 1800 (mean catch of 1-5 smelt per trawl). After 1980, the index was consistently less than 400 (mean catch of less than one smelt per trawl). The frequency of occurrence of delta smelt in the autumn trawls has also declined (Figure 3). Until 1981, delta smelt were found in 30 to 75 percent of the trawl catches. After 1981 they were never caught in more than 25% of the trawls.

The trends of decreasing numbers of delta smelt is reflected as well in the annual catch data from the CFG bay survey and the UCD Suisun Marsh survey, for which effort was more or less constant (Figure 4). In both surveys, delta smelt catch declined dramatically after 1981 and numbers have remained low. In the bay survey, delta smelt were caught in all months from 1981 through 1984 but

only in 9 months in 1985, 10 in 1986, 6 in 1987, and 5 in 1988. During the 11 year Suisun Marsh
ey, 468 delta smelt were collected, all but four before 1984, with a peak catch of 229 fish in
1981.

Because of its one-year life cycle, delta smelt abundance is potentially limited by egg production
of the previous year class. However, the wide year-to-year variability in abundance shown by this
species prior to its decline in 1981 shows little evidence of effect of parent population size on
subsequent recruitment. A spawner-recruit relationship based on the autumn midwater trawl data
from successive years explained only about one quarter of the year to year variability ($r2=.24$,
$n=19$). The weak stock-recruitment relationship suggests that environmental factors severely limit
delta smelt abundance, even in years of high population size.

Environmental factors

Delta smelt are most abundant in shallow, low salinity water associated with the mixing zone in
the estuary, except when they are spawning. In the bay survey, 62% of the catch of delta smelt in
Suisun Bay occurred at three stations less than 4 m deep. The remaining 38% were captured at six
deeper stations. The salinity profiles from the bay study show that most of the catches of delta smelt
occurred in Suisun Bay upstream of areas where there was a large difference between surface and
bottom salinities or in the channels of the lower Sacramento and San Joaquin Rivers (Figure 5). A
small peak in abundance regularly occurred downstream of the mixing zone at a shallow station
adjacent to a tidal marsh. Delta smelt were captured in salinities of 0 to 14 ppt (= 2 ppt, n =
281) and at temperatures of 6 to 23°C (= 15°C, n = 281). No relationship was found between
surface temperature at each station and delta smelt distribution, because temperature showed more
variation among months than between stations.

Between 1981 and 1984, the mixing zone was located in Suisun Bay during October through
March, except during months with exceptionally high outflows. During April through September, the
mixing zone was usually found upstream, in the channels of the rivers. Since 1984 the mixing zone
has been located mainly in the channels of the rivers during all months of the year, except during one
period of record outflow in 1986. This shift in the zone's location during winter coincides with an
upstream shift and narrowing of the location of the delta smelt population to the deeper water of the
main river channels (Figure 5).

The seasonal concentration of delta smelt in fresh water for spawning is shown by the change
in surface salinities at trawl sites where smelt were captured (Figure 6). After September they are
found in increasingly less saline sites. The capture in fresher water does not result in a change in
geographic distribution until several months later. From December to April (when young of year are
usually first caught), they are almost entirely restricted to freshwater.

Relationship of Abundance to Outflow

Movement of the mixing zone into river channels in the Delta is related to the sporadic decrease
in inflowing water during years of low precipitation and the steady increase in the proportion of fresh
water diverted each year and month by the pumps and canals of the State Water Project and federal
Central Valley Project. Since 1983, the proportion of water diverted during October through March
(first half of the official water year) has remained at high levels (Figure 7). Because high levels of
diversion pull Sacramento River water across the Delta and into the channel of the San Joaquin river
downstream of the pumps, the net movement of water in the lower San Joaquin River is upstream
during these periods (Figure 8). The number of days of net reverse flow of the lower San Joaquin
River has increased during periods of low outflow and in response to steadily increasing rates of
diversion. Until 1984 years with more than a hundred days of reverse flow happened quite
sporadically and seldom showed reverse flow during the delta smelt spawning season. In every year
since 1984, reverse flows have characterized the lower San Joaquin for more than 150 days of the
year and in every year except 1986 reverse flows have occurred for 15 to 85 days of the spawning
season (Figure 9). The restriction of the mixing zone to an area around the mouths of the rivers has,
therefore greatly increased the likelihood of displacement delta smelt. Reverse net flows in the
lower San Joaquin have been a constant feature of the delta recent years during the months when

delta smelt are spawning except during 1986 when a tropical storm produced the wettest month on record during what was otherwise a dry year.

The recent decline in delta smelt coincides with the increase in proportion of water diverted and the confinement of the mixing zone to a small area in the river channels. Low catches during the drought of 1976-1977 also coincided with record high proportions of water diverted. Increasing rates of diversion since the earlier drought have resulted in greater proportionate diversion during the more recent drought, so that for 1988 the amount of water diverted exceeded the amount flowing out to sea.

Despite the coincidence of increased diversion and delta smelt decline, the relationship between outflows and delta smelt abundance is not a simple one as it seems to be for other species (Stevens and Miller 1983). To see if delta smelt might be favored by moderate outflows, which would keep them in Suisun Bay, we regressed the autumn midwater trawl abundance index on delta outflow and delta outflow squared. Outflow2 would allow the regression values to decline if delta smelt abundance peaked at moderate flows and declined at high or low flows. No relationship was found; all values of r2 were less than 0.23, after running all possible two consecutive monthly subsets from February to June. These results may have been confounded by the fact that since 1982, most years have been unusually wet (1983) or unusually dry (1987-1991).

Discussion

The delta smelt is a species that is adapted to living in the mixing zone of the Sacramento-San Joaquin estuary where it feeds on copepods and other zooplankton concentrated there. Because it has a limited range, essentially a one-year life cycle, low fecundity, and planktonic larvae it is unusually sensitive to changes in estuarine conditions. This sensitivity has caused its population to remain extremely low since 1980. As Pimm et al. (1988) show, small species with variable populations, such as delta smelt, become increasingly vulnerable to extinction as their populations decrease. Thus, delta smelt fits the definition of an endangered species under the United States Endangered Species Act (US-ESA), as it is in danger of extinction throughout its limited range. Given its persistence through seven years of severe conditions, however, threatened status may be appropriate instead.

The US-ESA provides five general reasons why a species may be threatened or endangered: "(A) the present, or threatened, destruction modification, or curtailment of its habitat or range, (B) over-utilization for commercial, recreational, or educational purposes, (C) disease or predation, (D) inadequacy of existing regulatory mechanisms, or (E) other natural or manmade factors affecting its continued existence." There is no evidence that reasons B or C have reduced delta smelt numbers, but A,D, and E have all played a role. The other factors (E) affecting its existence include toxic compounds in the water, changes in its food supply, and competition from introduced species.

Destruction of habitat. The principal habitat of the delta smelt is the shallow waters of the Delta and Suisun Bay. To provide sufficient food for these fish, the water must contain dense populations of zooplankton, especially copepods. This means an apparently crucial habitat requirement for these fish is a mixing zone located in Suisun Bay during March-June, when larval smelt are present. When the mixing zone is in Suisun Bay, optimal conditions for delta smelt occur over a much larger total area that includes extensive shoal areas than when the mixing zone is located upstream. The river channels in the Delta are comparatively small in surface area and have few shoal areas, so provide little favorable habitat for delta smelt. Because the delta smelt is essentially an annual fish with relatively low fecundity, a food-rich area with extensive shallow areas immediately downstream from its spawning areas must have been a consistent part of its environment during most of its evolutionary history.

Increasing diversion of fresh water from the estuary has altered the location of the mixing zone, as well as flow patterns through the Delta during most months of the year. The shift of the mixing zone to river channels not only decreases the amount of suitable habitat for delta smelt but results in decreased phytoplankton and zooplankton production (Herbold and Moyle 1989). During the months when delta smelt are spawning, the changed flow patterns presumably lead to greater rates of entrainment of both spawning adults and newly hatched larvae into water diversions. The combined

effects of habitat constriction and fish entrainment due to increasing rates of diversion provide the most likely mechanism to explain the decline in delta smelt abundance.

This problem has no doubt been exacerbated by the near-drought conditions that have existed in the drainage since 1987, coupled with the record high outflows that occurred in February 1986 (which flushed fish out of the estuary). However, since 1984 the percentage of inflow diverted has been higher and stayed higher for longer periods of time than during any previous period, including the severe 1976-1977 drought. This was true even in 1986 because the record precipitation occurred during a very short period, after which the system returned to drought conditions, although outflows through the Delta were kept high by water released from upstream reservoirs.

Inadequacy of existing regulatory mechanisms. The regulation of Delta outflows, Delta water quality, and flow patterns through the Delta is complex and under the jurisdiction of a number of agencies (Herbold and Moyle 1989). The present regulatory system primarily benefits water exporters at the expense of fish and other estuarine-dependent organisms (Nichols et al. 1986). Even valuable sport and commercial fishes such as striped bass and chinook salmon have suffered major declines in recent years, despite efforts to sustain them. Large numbers of pelagic fishes, especially larvae, are entrained in water diversions of the Federal Central Valley Project, the State Water Project, Delta agriculture, power plants of Pacific Gas and Electric Company, and other industry. Present rescue and mitigation efforts do not seem to compensate for the losses. This is particularly true of delta smelt which (1) are frequently exposed to entrainment (Stevens et al. 1990), (2) are unlikely to survive any rescue attempts that involve handling of fish (authors, personal observation), and (3) have received little attention from management agencies until recently. In short, the present mechanisms that regulate freshwater flows through the estuary do not adequately protect delta smelt.

Toxic compounds. Pesticides in the lower Sacramento River at concentrations potentially harmful to fish and zooplankton have been recorded in recent years (Jung et al 1984; Foe 1989). Pesticides also enter the Delta from agricultural operations on Delta islands and from the San Joaquin River, while heavy metals and other pollutants enter from urban areas. The effects of toxic compounds on delta smelt is unknown, but they have apparently occurred at high levels in fresh water before the most recent decline of delta smelt. The concentration of delta smelt in the mixing zone may reduce the effects of toxics, because of the dilution of contaminated fresh water by inflowing seawater. However, the intensive agriculture practiced on Delta islands and in the Central Valley means that toxic agricultural chemicals always have the potential of contributing to delta smelt decline.

Changes in food supply. Delta smelt feed primarily on copepods so changes in copepod abundance may affect smelt abundance. In 1988, the abundance of Eurytemora affinis, the principal food of delta smelt in 1972-1974, declined precipitously. Increases in the abundance of two exotic copepod species have partly compensated for this decline. The invasion of Sinocalanus doerrii occurred in 1978-1979 (Orsi et al. 1983), before the delta smelt decline, and the invasion of Pseudodiaptomus forbesi apparently occurred around 1986, after the decline (J. Orsi, CDFG, Stockton personal communication). Although S. doerii is apparently rarely eaten by smelt, P. forbesi is now a major part of their diet. The shift in copepod species does not appear to have had a major effect on delta smelt populations because delta smelt were able to shift their diet to the new species. However, P. forbesi peaks in abundance later in the year than does E. affinis, so there may now be periods in the spring when copepods are not as available as they once were to larval smelt.

Competition from introduced species. The Sacramento-San Joaquin estuary has a long history of invasions by introduced fishes and invertebrates (Herbold and Moyle 1989). The delta smelt seems to have been relatively unaffected by them, including the invasion of a planktivore, the inland silverside (Menidia beryllina) in 1975 (Meinz and Mecum 1977). The major changes in the estuary that have taken place in the past several years have led to a new influx of invaders, including one species of fish, four species of copepods, an amphipod, and a clam. The ballast-water introduction of the Asiatic clam Potamocorbula amurensis occurred about 1987 and it now occurs in extraordinarily high densities in Suisun Bay (Carlton et al. 1990). The high densities and filtration rates of the clam may be the cause of the extremely low densities of phytoplankton and zooplankton that have been observed there recently. The invasion of the clam took place after the decline of delta smelt, but the clam's

presence may make delta smelt recovery more difficult if low zooplankton densities continue. Whether or not the clam or other recent invaders will be able to persist if freshwater outflows increase again is not known.

Conclusion

Regardless of cause, the consistently low population of delta smelt in recent years indicates that immediate action is needed to reduce the probability of it becoming extinct. In the past, the delta smelt population has shown extreme fluctuations from year to year, as might be expected of an annual species with pronounced habitat requirements in a highly disturbed system. The population is presumably continuing to fluctuate, but at such low numbers the fluctuations cannot be reliably detected using the present methods. With such low numbers, the delta smelt population may well fluctuate into extinction in a single year (Pimm et al. 1988).

The first step is to have delta smelt officially recognized as threatened or endangered at both the state and federal levels, followed by a research program aimed at determining the ecological requirements of delta smelt, particularly of their early life history stages. Reducing the effects of water diversions and restricting ship ballast water discharges to minimize further invasions of exotic species are crucial to preserving this species. Protection of delta smelt would likely benefit other species with pelagic larvae whose numbers have shown severe declines in recent years, including striped bass and longfin smelt. The monitoring program for delta smelt should be expanded. Because the delta smelt has a one-year life cycle, the status of its populations would be a good barometer of the health of the upper Sacramento-San Joaquin estuary.

Acknowledgments

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Table 1. Diet (percent volume) of delta smelt in 1972-1974 and in 1988.

Food Category	1972				1973								1974					1988
	Sep	Oct	Nov	Dec	Jan	Mar	Jun	Jul	Sep	Oct	Nov	Dec	Jan	Feb	Apr	Jul	Nov	Dec
Mean SL (mm)	61	67	63	60	64	62	58	41	51	56	58	60	61	65	65	44	58	61
n	23	20	23	30	50	64	5	15	129	84	60	60	44	72	25	161	23	16
% Empty	43	10	50	27	40	16	0	20	16	23	0	23	20	0	0	42	19	0
Copepoda*	39	5	98	84	37	23	100	88	81	81	87	28	17	85	22	69	100	82
Neomysis mercedis	58	95	1	16	43	12	--	3	14	14	1	8	6	14	--	23	--	--
Corophium spp.	--	--	--	--	--	--	--	6	5	5	10	13	4	1	2	2	--	1
Gammaridae	--	--	--	--	13	1	--	--	--	--	--	--	--	--	--	--	--	<1
Daphnia	3	--	<1	--	1	34	--	--	--	--	--	12	4	--	13	--	--	2
Bosmina	--	--	--	--	--	--	--	--	--	--	2	33	68	--	59	--	--	13
Chironomidae	--	--	--	--	4	30	--	--	--	--	<1	4	<1	--	--	--	--	2
Others	--	--	--	--	2	--	--	3	--	--	--	2	1	--	--	--	--	-

*Copepods were mainly Eurytemora affinis in 1972-1974 and Pseudodiaptomus forbesi in 1988.

Figures

Figure 1. Historic range of delta smelt in the Sacramento-San Joaquin estuary. Smelt have been found regularly in Suisun Bay. Years of high outflow have distributed smelt as far downstream as San Pablo Bay. Upstream limits, occurring usually during the smelt's spawning migration in spring, are at Mossdale on the San Joaquin River and Sacramento on the Sacramento River.

Figure 2. Trends in total delta smelt catches from two sampling programs encompassing more than twenty years each throughout the historic range of delta smelt but during a limited part of each year. The DFG fall midwater trawl samples were taken from September to December of most years since 1967 in deep water habitats throughout most of the historic range of delta smelt. Summer townet surveys sample midwater populations of smaller fishes during the months of June and July. The Summer townet survey began in 1959 and provides data on smelt abundance for all years except 1966-1967.

Figure 3. Mean frequency of occurrence (circles) and ranges (vertical lines) per trawl of delta smelt in autumn midwater trawl surveys, 1967-1988.

Figure 4. Trends in total delta smelt catches from two monthly sampling programs in the lower Sacramento-San Joaquin estuary through the ten years following 1979. Suisun Marsh has been sampled monthly since 1979 and is a shallow water habitat near the middle of the delta smelt's historic range. The DFG Bay Study has sampled shallow and deep water habitats monthly since 1980 in the western half of the delta smelt's historic range.

Figure 5. Location of delta smelt catches in relation to the mixing zone and areas in the Sacramento-San Joaquin estuary during the periods before (January 1981 - September 1984) and after (October 1984-December 1988) the collapse of delta smelt populations. The mixing zone is indicated by large differences between salinities in surface and bottom waters in upstream areas. Lines represent mean catch per station of delta smelt and bars represent the difference between bottom and surface salinities. Upstream stations are to the right.
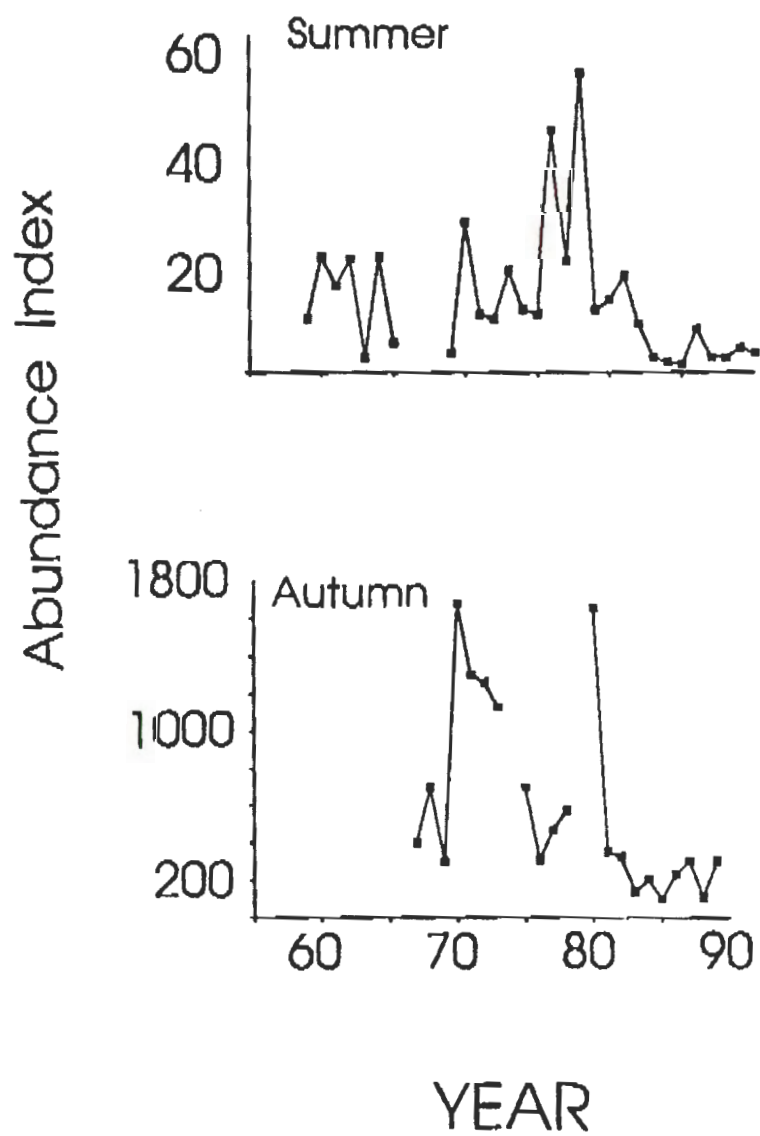
Figure 6. Mean (± 1 SE) surface salinity in stations in which delta smelt were captured (lower solid line) compared to stations where they were not captured (upper broken line), on a monthly basis, 1981-1984.
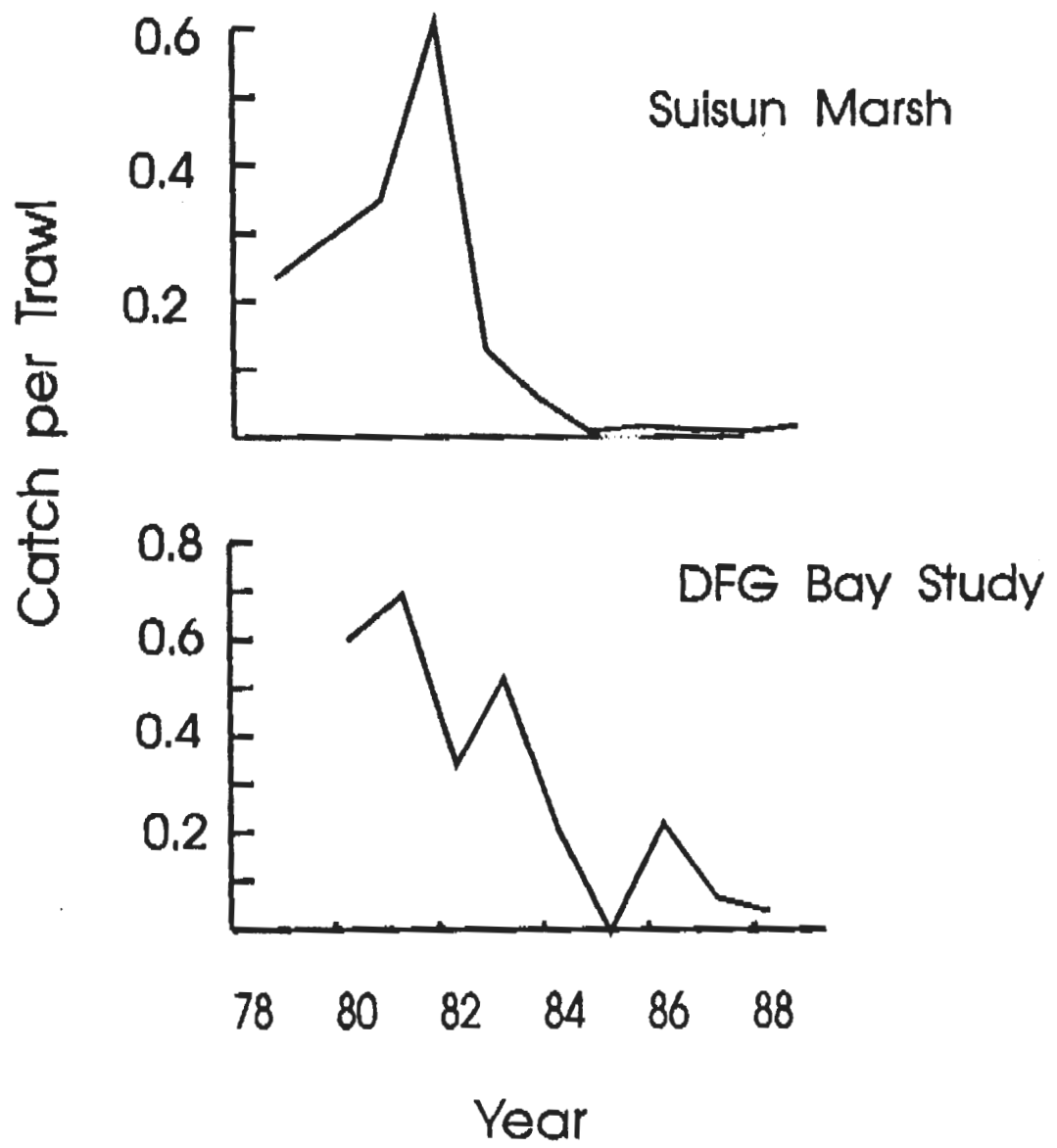
Figure 7. Proportion of water flowing into delta exported from pumping plants in south delta, by quarter. Water year is from October to September, with October to March being the wettest period.
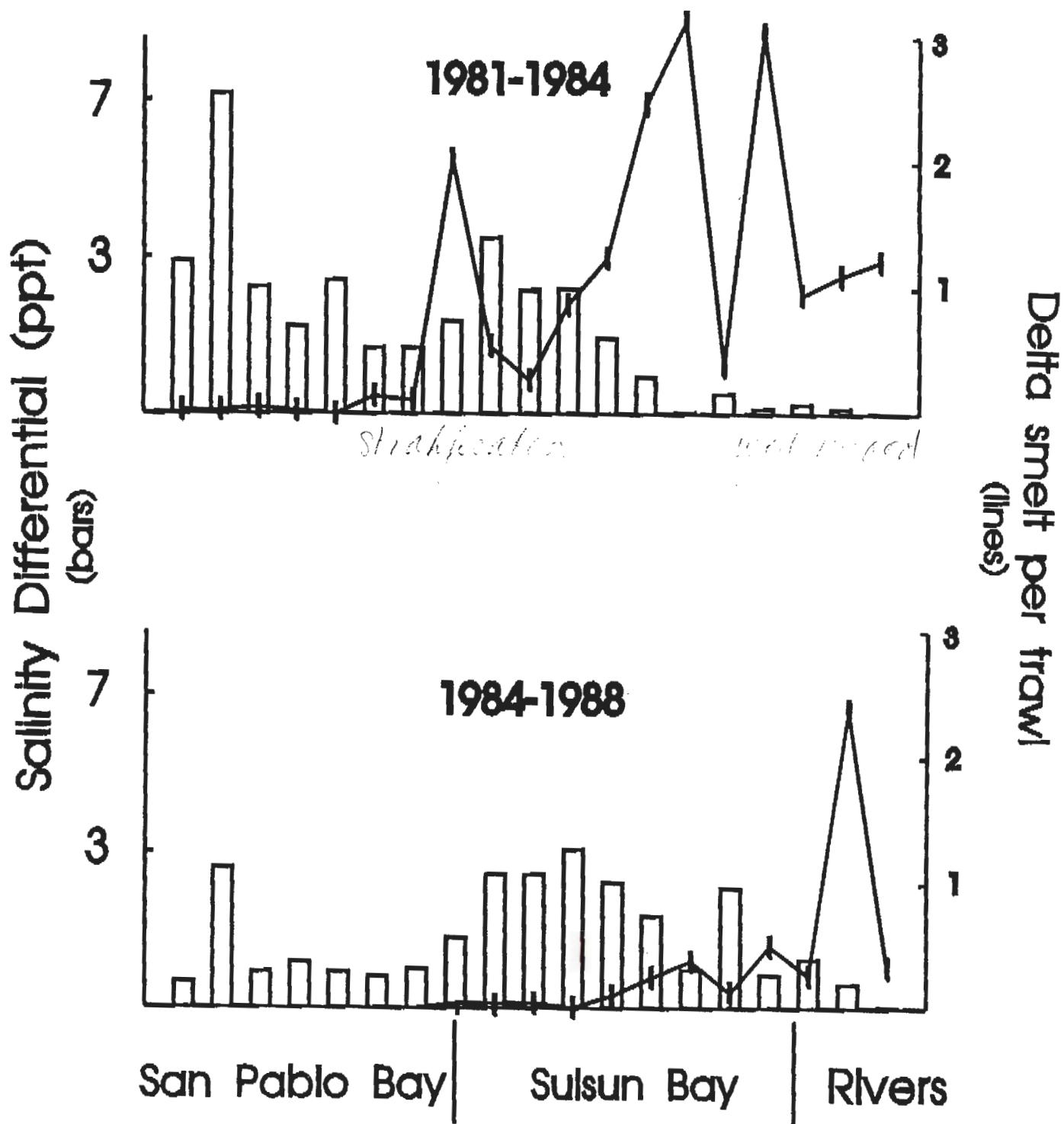
Figure 8. The Sacramento-San Joaquin estuary showing the directions of water flow during periods of high diversions. These conditions were formerly described as "typical summer flow patterns" (Herbold and Moyle 1989), but have been common in all months since 1984. Note the flow of Sacramento River water across the Delta and the net reverse flow of the lower San Joaquin River.
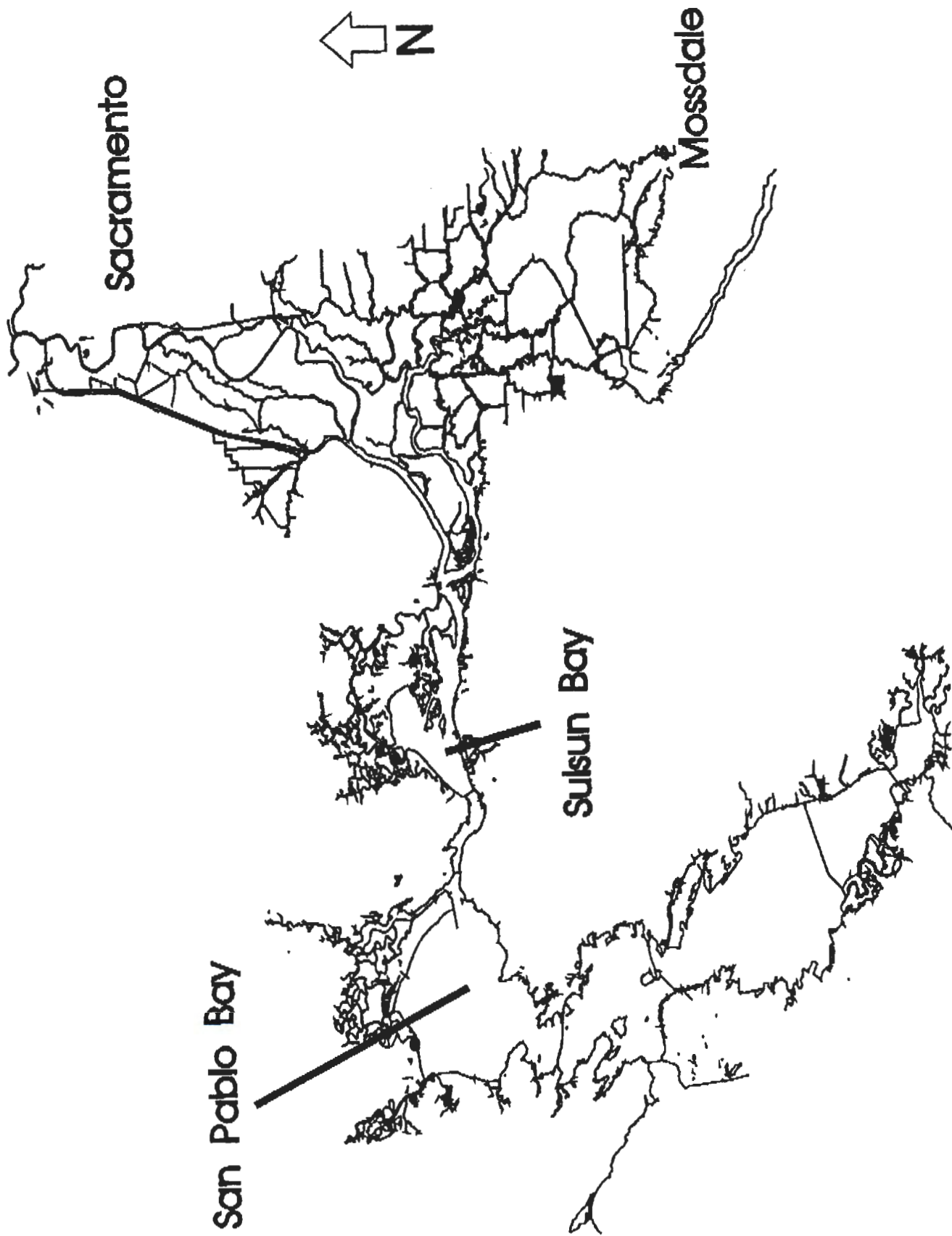
Figure 9. Number of days of net reverse flow in the San Joaquin River during the spawning season of delta smelt (February-May) and the rest of the water year (October of preceding year - January, and June-September) half of each water year, 1956-1988.
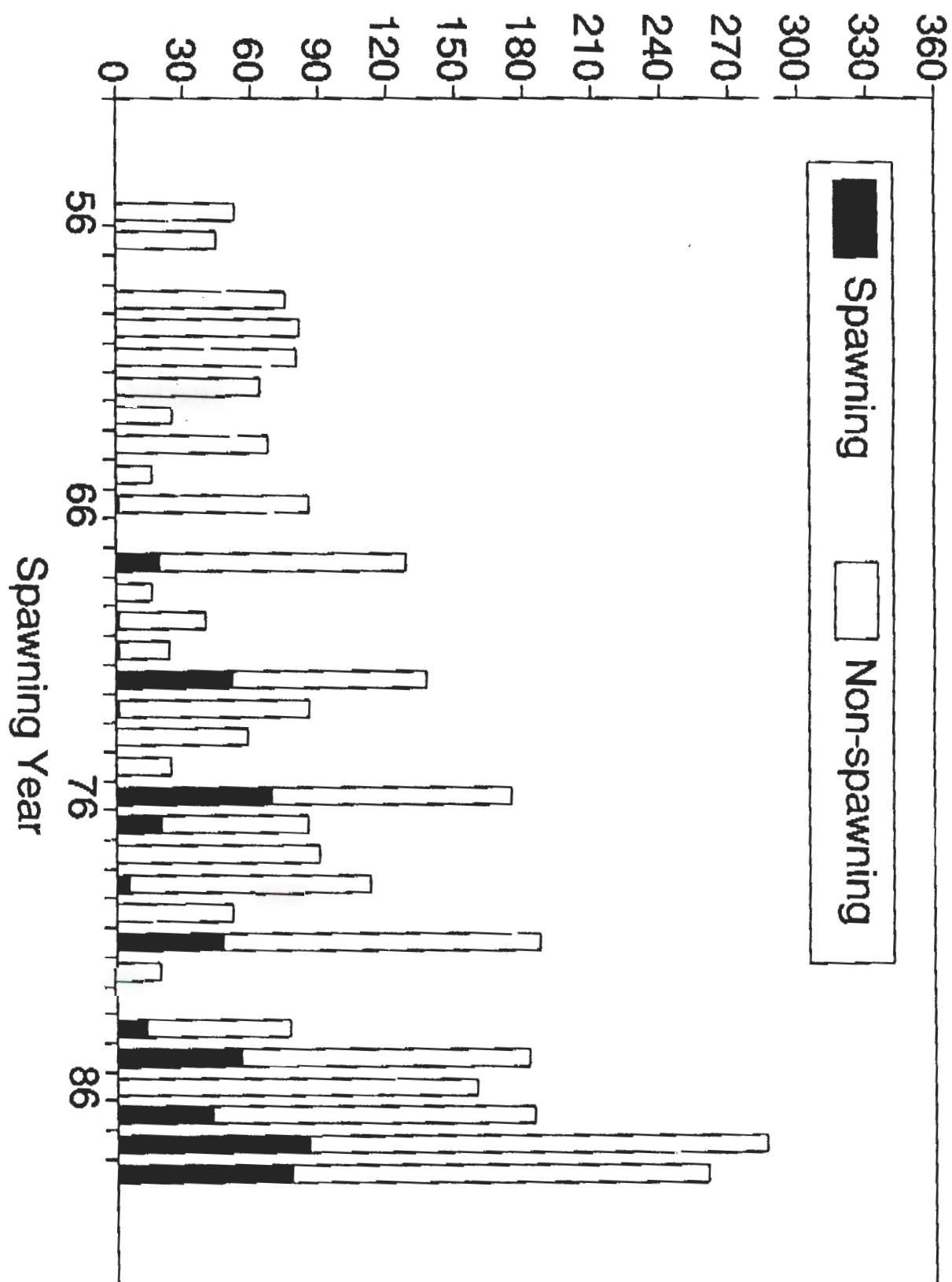
N

Sacramento

Sacramento River

Suisun Bay

San Joaquin River

Tracy

Mossdale

1981-1984

1984-1988

Salinity Differential (ppt) (bars)

Delta smelt per trawl (lines)

San Pablo Bay | Suisun Bay | Rivers

Sacramento

Mossdale

N

Suisun Bay

San Pablo Bay
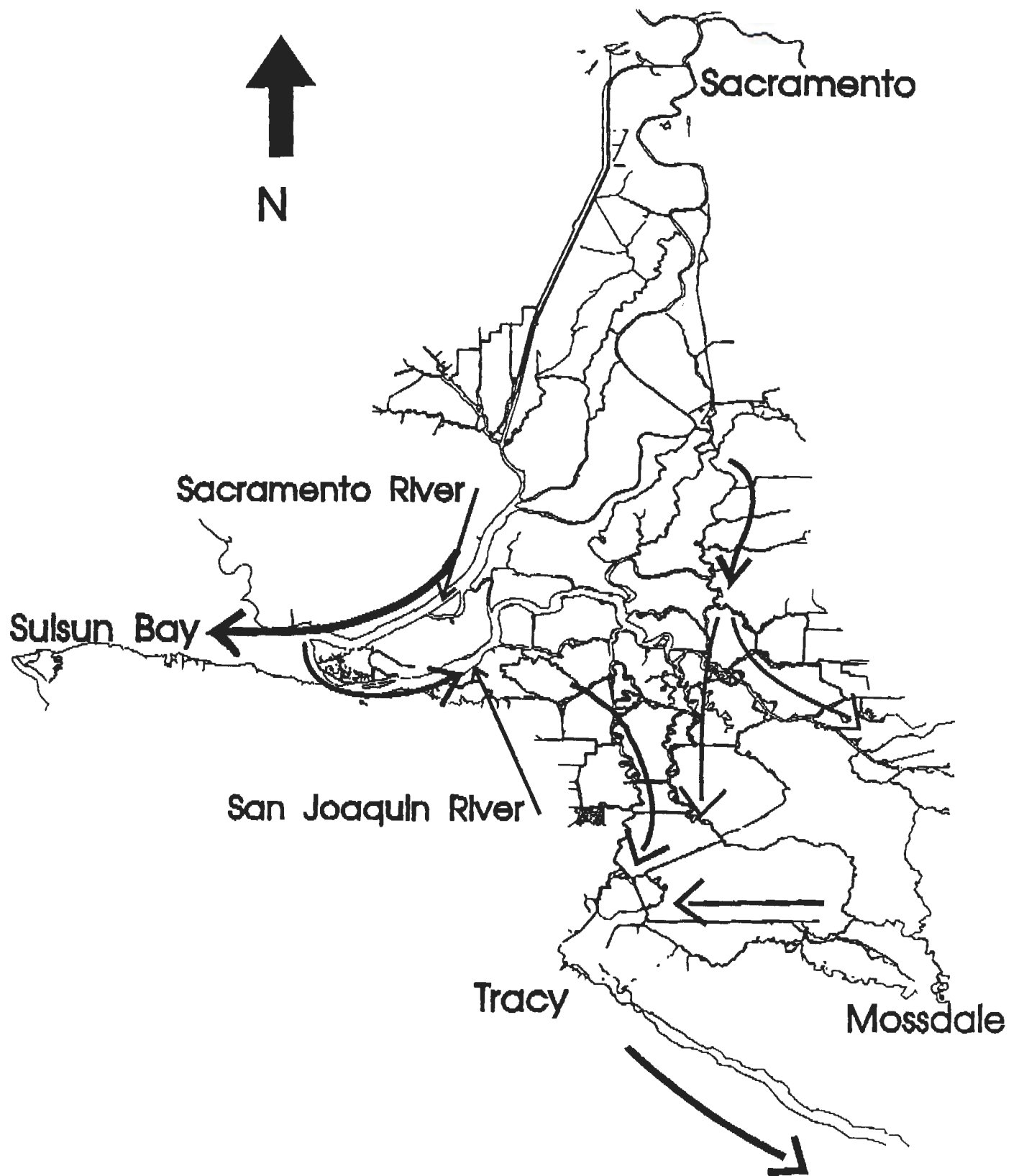
Number of Days of Net Reverse Flow vs. Spawning Year

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FACTORS INFLUENCING THE ENTRAPMENT OF SUSPENDED MATERIAL IN THE SAN FRANCISCO BAY-DELTA ESTUARY

JAMES F. ARTHUR AND MELVIN D. BALL

U. S. Bureau of Reclamation, 2800 Cottage Way, Sacramento, CA 95825

Inorganic suspended particulate matter, turbidity, particulate nutrients, phytoplankton, *Neomysis mercedis* (Holmes), certain other zooplankton, and juvenile striped bass (young-of-the-year) accumulate in an entrapment zone located in the upper San Francisco Bay-Delta estuary (Sacramento-San Joaquin River System). The location of this entrapment zone is regulated by the magnitude and the pattern of river inflow, as well as the tidal excursion. At Delta outflow indices of 20 $m^3 \cdot s^{-1}$, the zone was located 40-45 km upstream of its location at 1,800 $m^3 \cdot s^{-1}$; tidal movement of the zone is from 3 to 10 km, depending on tidal phase and height. The location of the zone is related to, and can be approximated from, specific conductance values of 2 to 10 millimho·cm^{-1} (1-6 °/oo salinity). The concentration of constituents in the zone varied directly with Delta outflow, water depth, and tidal velocity. Depending on the constitutent and environmental conditions at the time of measurement, the suspended-material concentration varied from as little as twice to as much as several hundred times the upstream or downstream concentration. The most significant environmental aspect of the entrapment zone may be that the quantity of phytoplankton and certain other estuarine biota appear to be enhanced when the zone is located in upper Suisun Bay.

Bureau of Reclamation (USBR) and the California Department of Water Resources (DWR) plans call for large pumped diversions from the southern portion of the Sacramento-San Joaquin Delta and possible construction of a drain (for removal of saline subsurface agricultural water from the San Joaquin Valley) which may discharge in the general vicinity of Suisun Bay.

The USBR is cooperating with the U. S. Fish and Wildlife Service (USFWS), the California Department of Fish and Game (DFG), and DWR in conducting environmental studies ("Interagency Ecological Study Program") to evaluate the potential impact of these projects on the estuary. This chapter describes one aspect of this program: the determination of how changes in Delta outflow and flow patterns, attributable to the operation of the federal and state water projects, might influence the distribution and abundance of estuarine phytoplankton and other particulate material (Ball 1977; Arthur and Ball 1978). Among the factors evaluated thus far, the entrapment zone appears to be a major feature regulating the phytoplankton standing crop in Suisun Bay (Arthur 1975; Arthur and Ball 1978).

BACKGROUND

Phytoplankton are important to the estuarine environment as primary producers, with certain species forming the base of the food web. However, in many aquatic environments, excessive concentrations of phytoplankton cause eutrophication (i.e. reductions in dissolved oxygen concentrations to a point detrimental to higher aquatic organisms), create taste and odor problems in municipal water supplies, clog filters in water treatment plants and/or are aesthetically undesirable for recreationists. However, phytoplankton problems presently appear minor and the maximum desirable concentration and species composition of phytoplankton has yet to be determined

(Arthur and Ball 1978) in the study area (Fig. 1).

The quantity of freshwater flowing through the estuary is important to phytoplankton growth because it regulates nutrient concentration, determines riverborne sediment inflow and influences suspended-particle transport which in turn affects light-penetration (required for algal growth), determines phytoplankton residence time, and directly regulates salinity intrusion and
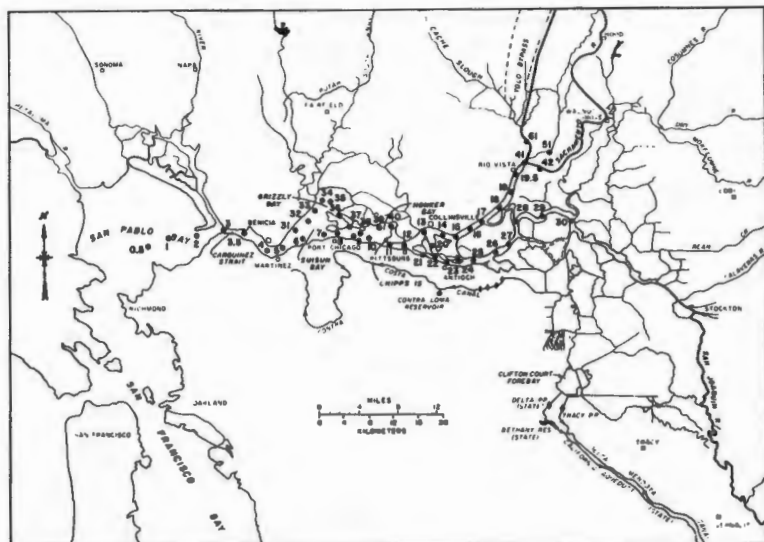

Fig. 1. Sampling sites of entrapment zone study.

the location of the entrapment zone. These and other factors interact to determine the amount and type of phytoplankton in the estuary (Arthur and Ball 1978). Ball (1977) and Ball and Arthur (1979) have evaluated factors influencing the temporal and spatial distribution and abundance of phytoplankton throughout the San Francisco Bay-Delta estuary.

Krone (1966, 1979), among others, has speculated that under projected low flow conditions resulting from water development projects the sediment input to the estuary would be greatly reduced, resulting in a greater photic depth in Suisun Bay. This increase in photic depth could potentially increase the phytoplankton standing crop to undesirable concentrations.

In evaluating the probable effects of subsurface agricultural drain discharge to the estuary, Bain (1968) concluded that this discharge would about double the concentration of nitrogen in Suisun Bay which could result in severe algal blooms accompanied by depressions in dissolved oxygen as the blooms decline. As a result, methods were studied for removing nitrogen from drainage water (Brown 1975) and studies were conducted on the potential impact of drain water on the Delta environment (USBR 1972).

In reviewing water quality data and factors controlling phytoplankton growth during the 1968-74 period (Arthur 1975; Ball 1975, 1977), long-term averages of phytoplankton, chlorophyll, particulate organic nitrogen and particulate phosphate, turbidity, and inorganic suspended solids were found to be at higher concentrations in Suisun Bay than in the adjacent upstream or

downstream areas. Since phytoplankton concentrations were highest in Suisun Bay, while light penetration was lowest and water temperatures and nutrient concentrations were generally favorable, some other mechanism(s) apparently was responsible for the high phytoplankton concentrations.

Further evaluation of other historical water quality data and review of suspended-materials distribution studies for the area (for example, Simmons 1955; Einstein and Krone 1961; Meade 1972; Peterson and Charnell 1969; Conomos and Peterson 1974, 1977; Peterson et al. 1975a,b) and for other estuaries (Wiley 1977) has led us (Arthur 1975; Ball 1977; Arthur and Ball 1978) to conclude that suspended materials are entrapped and accumulate in the estuary at the upstream end of the fresh-water—salt-water mixing zone. We theorize that the causes of this entrapment are the increased flocculation, aggregation, and/or settling of suspended materials at specific conductances above 1 millimho/cm (0.6 °/∞ salinity) and the effects of net two-layered estuarine circulation flow (California DFG et al. 1975, 1976). Terms used by others to describe the area of maximum concentration of suspended materials are the "turbidity maximum," "critical zone," "nutrient trap," "sediment trap" and "null zone" (Arthur and Ball, 1978). We prefer the more descriptive "entrapment zone" (Arthur 1975).

Studies in the San Francisco Bay-Delta Estuary

As early as 1931, Grimm stated there were net upstream bottom currents in the San Francisco Bay Estuary. Since then, studies (Simmons 1955; U. S. Army Corps of Engineers 1967, 1977; Smith 1966; McCulloch et al. 1970; Conomos 1975, 1979; Conomos et al. 1970, 1971; Conomos and Peterson 1974; Peterson et al. 1975a) have demonstrated that a net two-layered flow circulation pattern exists throughout much of the northern reach of the Bay system. This generalized flow is believed to be significantly modified by "trapping" and "pumping" (two forms of tidal dispersion) and wind dispersion (Fischer 1976).

The location of the entrapment zone, the effects of riverflow on its location, and seasonal changes in the abundance and composition of suspended matter in the zone have been described (Conomos and Peterson 1974; Peterson et al. 1975a, b; Arthur 1975; Ball 1977; Arthur and Ball 1978). These and other studies produced a reasonably good understanding of how two-layered flow influences sediment transport in this and other estuaries.

In contrast, very little is known about the effects of two-layered flow on the estuarine biota. Although no specific studies were conducted on the effects of two-layered flow on the plankton and benthos in the entrapment zone, an early conclusion (Kelley 1966) was that of the environmental factors studied, chlorinity (salinity) was most responsible for species distribution of zooplankton and zoobenthos. Recent evaluations (Arthur 1975; Arthur and Ball 1978; Siegfried et al. 1978; Orsi and Knutsen 1979) indicate that zooplankton entrapment occurs. Riverflow and salinity were considered the dominant factors controlling longitudinal distribution of a number of species of fish in the estuary (Turner and Kelley 1966). Furthermore, the maximum concentration of juvenile striped bass (young-of-the-year) are known to occur within specific salinity ranges (Turner and Chadwick 1972; Stevens 1979).

The summer phytoplankton and zooplankton maxima were observed in the entrapment zone (Conomos and Peterson 1974; Peterson et al. 1975a,b; Arthur 1975; Ball 1977; Arthur and Ball 1978).

ESTUARINE HYDRODYNAMICS AND SUSPENDED MATERIAL TRANSPORT

The study area is considered an estuary characterized by two-layered flow with appreciable vertical mixing during most of the year (Conomos 1979). According to Bowden (1967), estuaries

having such flow and mixing are generally shallow. The tidal currents are of increasing amplitude and extend throughout the depth mixing the fresher water downwards and the more saline water upwards. Although vertical mixing occurs, there are still two layers of net flow separated by a plane of no-net-motion which is generally above mid-depth (Fig. 2). The salinity continuously increases from the water surface to the bottom with the maximum salt gradient occurring at the plane of no-net-motion.
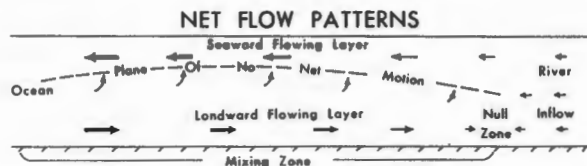
NET FLOW PATTERNS

Fig. 2. Theoretical net flow patterns in a two-layered flow with vertical mixing estuary.

A wide range in water stratification exists in this type of estuary and is dependent on the ratio of the amplitude of tidal currents to the riverflow and depth. The increase in salinity from surface to bottom may vary from 1 to 10 °/oo (specific conductance of approximately 1.5 to 15 millimho·cm⁻¹). The net seaward flow of the upper layer may be several times the river inflow (Bowden 1967).

The primary driving force causing the net upstream flow in the lower layer of water is the salt-induced density difference between the surface and bottom waters (Fig. 3). Because of this density difference, freshwater entering the estuary with a greater hydraulic head tends to flow over the denser, more saline water (Simmons 1955; Schultz and Simmons 1957; Helliwell and Bossanyi 1975; Krone 1972). The greater the river inflow, the greater the hydraulic head or vertical gradient and, consequently, the greater the seaward-driving force. High river flows drive the mixing zone of freshwater and seawater farther seaward, increase salinity stratification, and compress the mixing zone (Arthur and Ball 1978; Conomos 1979). The turbulent forces of tides and winds tend to destroy vertical salinity stratifications (Nichols and Poor 1967; Conomos 1979).

The two-layered flow theoretically influences the maximum tidal-current velocities of each layer. Because there is a net downstream flow in the surface layer, surface velocities are greater
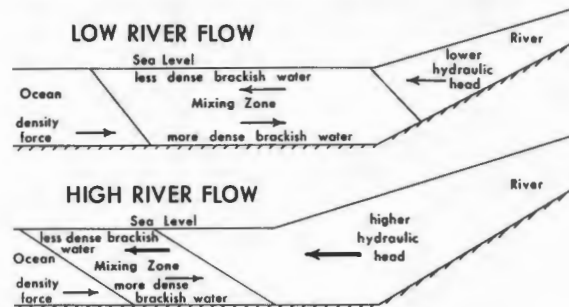
Fig. 3. The primary driving forces controlling two-layered flow circulation in the estuary.

during ebb tides than during flood tides, while in the lower layer, the reverse occurs. Higher velocities occur during flood tides than during ebb tides and increase the net upstream transport of materials along the bottom (Postma 1967).

Several factors influence the transport of suspended materials (Fig. 4). In our laboratory studies we have demonstrated that increasing the salinity of Delta water (starting at about 1.0 millimho/cm specific conductance [0.6 °/oo]) enhances flocculation of the suspended inorganic particles (primarily in the 2- to 10-μ size range) into aggregates. These aggregates settle at rates

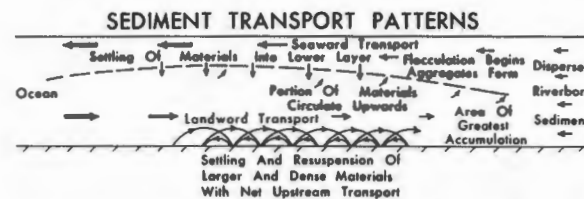## SEDIMENT TRANSPORT PATTERNS

Fig. 4. Theoretical transport patterns of suspended materials in a two-layered flow with vertically mixing estuary.

greater than the unaggregated materials and are transported downstream out of the estuary or settle into the lower layer and are returned upstream where they concentrate in the entrapment zone (Simmons 1955; Krone 1966; Meade 1972; Conomos and Peterson 1974, 1977). Larger and denser materials may settle out near slack tides and then be resuspended as tidal velocity increases. The less dense and smallest suspended materials tend to be carried into the upper layer as a result of the net upward vertical flow and are transported seaward. A portion of the suspended material is transported laterally into shallow areas and may be deposited in shoals. Some of the sedimented materials may be resuspended by tidal or wind action and transported back to the channel. Suspended materials in the lower layer may be transported upstream to the entrapment zone where the areas of maximum concentration and maximum water residence time occur. Theoretically the entrapment zone occurs slightly downstream of where the net vertical water velocities are thought to be the greatest. As the aggregates move into the fresher water, partial disaggregation may occur. The materials that enter the upper layer are again transported seaward and theoretically can be recirculated numerous times. Under low riverflows, suspended sediment settles into the lower layer farther upstream in the estuary than during high flows. Conversely, during high riverflows, a larger portion of the fine suspended sediment is transported to the ocean.

FIELD OBSERVATIONS

Studies conducted from 1973 through 1977 (Arthur and Ball 1978) and summarized in this chapter were designed to characterize the distribution of suspended materials in the entrapment zone over a range of river discharge in order to determine how the zone influences the water quality and biota (primarily the phytoplankton).

River Discharge

Delta outflow (river discharge past Chipps Island, site 11) was the main variable in the study.

Daily Delta Outflow indices (DOI), calculated by the USBR and DWR, were used in this study. The DOI consists of the Sacramento River discharged at Sacramento plus the San Joaquin River discharge at Vernalis, less the pumped Delta export and the estimated Delta consumptive use (see Conomos 1979, Fig. 11). The consumptive use coefficient estimate varies seasonally but is constant between years. The coefficient is as high as 130 $m^3 \cdot s^{-1}$ in midsummer. Consequently, since crop and weather patterns change between years, under very low flows the DOI lacks precision. This error during typical summer outflow conditions may be as great as ±30 to 60 $m^3 \cdot s^{-1}$. Furthermore, the Yolo Bypass (which has tidally influenced discharge that would be hard to measure) and other peripheral streams also contribute significant discharges to the Delta outflow especially during periods of high runoff (over 1,400 $m^3 \cdot s^{-1}$). Measurements of these additional stream discharges are not included in the DOI but have been incorporated into another calculated outflow (average monthly historical Delta outflow) which still utilizes the consumptive use estimate. The historical Delta outflow, although only a monthly average, is the more accurate of the two for total discharges from the Delta (Fig. 5). Since the DOI is the only daily calculation readily available, the index is usually used when referring to Delta outflow even though it is an underestimate of high flow.
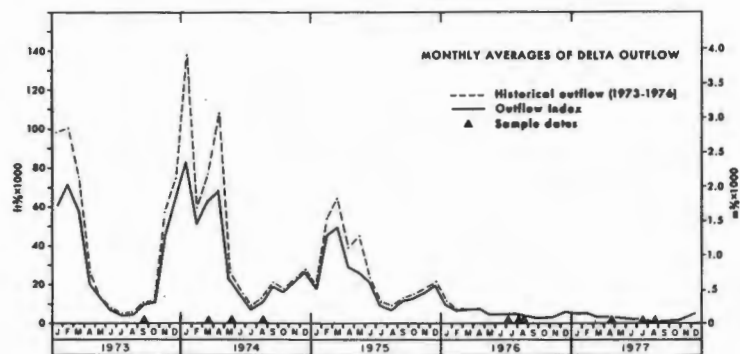
Fig. 5. Comparison of the Delta outflow index and the historical Delta outflow during the study period.

The Delta outflow during the 1973 through 1975 period was above normal, while during 1976 and 1977 it was the lowest since completion of Shasta Reservoir (the main water storage reservoir of the Central Valley Water Project).

Salinity Intrusion

The 2 millimho/cm specific conductance (1 °/oo salinity) isocontour shifted nearly 45 km over the range of DOI studied (23-1,800 $m^3 \cdot s^{-1}$) (Fig. 6).

In addition to the quantity of the riverflow, the pattern of flow also appears to influence the salinity distribution. For example, although the September 1973 and August 1974 surveys were conducted at near identical Delta outflows, there was greater compression of the 2-25 millimho·cm⁻¹ (1 to 15 °/oo salinity) water mass in 1973. There had been several months of low flow (the average DOI for July and August was 130 $m^3 \cdot s^{-1}$) prior to September 1973; while prior to the

August 1974 survey the DOI was nearly twice as large (Fig. 5).

Salinity stratification increased with increasing Delta outflow. The isoconductivity contours in March 1974 demonstrated greater vertical stratifications than during the low outflow of August 1977 (Fig. 6). The degree of stratification apparently also influences the distribution patterns of suspended materials.
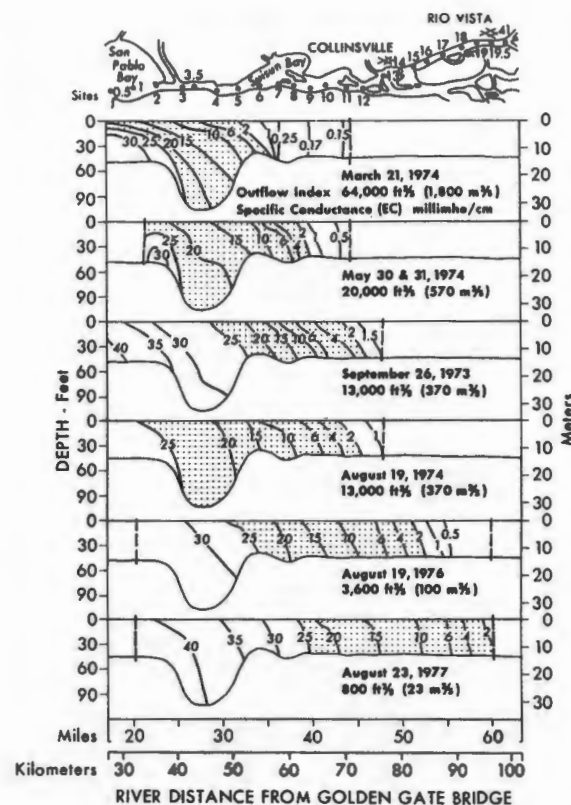

Fig. 6. Isoconductivity (salinity) contours measured on high slack tides at various Delta outflows (the 2-25 millimho/cm EC range has been arbitrarily shaded).

Typical variations in tidal excursion that occur in the study area are demonstrated for the 19-21 August 1974 and the 23 August 1977 data (Figs. 7, 8). The 1974 data were collected on three consecutive days with DOI = 370 $m^3 \cdot s^{-1}$, while the 1977 data were collected on a single day at DOI = 23 $m^3 \cdot s^{-1}$. The tidal excursion measured for the August 1974 run was nearly 10 km and occurred on a greater flood, close to a spring tide (with relatively high tidal velocities). Conversely, the tidal excursion for the August 1977 observations was only about 3 km. The reduced excursion
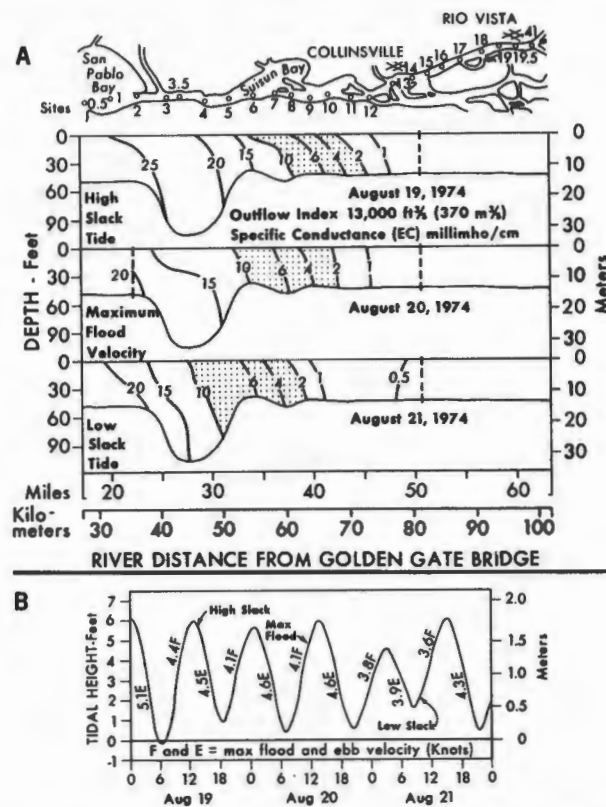
Fig. 7. A. Isoconductivity (salinity) contours measured on three consecutive days during different tidal phases during August 1974. B. Calculated Golden Gate Bridge tidal heights and maximum flood and ebb (F and E) velocities in knots.

resulted from the low tidal velocities and the slight difference in tidal heights occurring on the lesser ebb near a neap tidal period.

Suspended Material Distributions

The distribution patterns of suspended particulate matter and dissolved constituents were characterized in the upper estuary at selected DOI ranging from 23 to 1,800 $m^3 \cdot s^{-1}$ between September 1973 and September 1977 (Arthur and Ball 1978).

Total suspended solids (TSS) correlated well with turbidity, the latter of which was measured more extensively. Areas of maximum turbidity at various Delta outflow were typically located where the surface water was in the 2-10 millimho·cm^{-1} specific conductance (1-6 °/oo salinity)

range in both the Sacramento and San Joaquin rivers (Figs. 9 and 10). Because suspended materials accumulated in this salinity range, the 2-10 millimho·cm^{-1} surface specific conductance contour (SUR EC) was added to the illustrations as a reference.

The maximum turbidity in the entrapment zone varied from 2 to 40 times the upstream and downstream levels and increased up to 20 times with depth. The maximum turbidity, over 800 Formazin turbidity units (FTU; USEPA 1971) was centered in Carquinez Strait during the highest Delta outflow studied (1,800 $m^3 \cdot s^{-1}$) was centered in Carquinez Strait during the highest Delta outflow studied (1,800 $m^3 \cdot s^{-1}$). In contrast, during 1977 (one of the lowest river discharge years on record), maximum turbidities of about 60 FTU were measured at DOI = 23 $m^3 \cdot s^{-1}$ and the entrapment zone was centered about 40 km upstream of Carquinez Strait.

Volatile suspended solids (VSS) also peaked in the entrapment zone and were approximately 10-20% of the TSS.
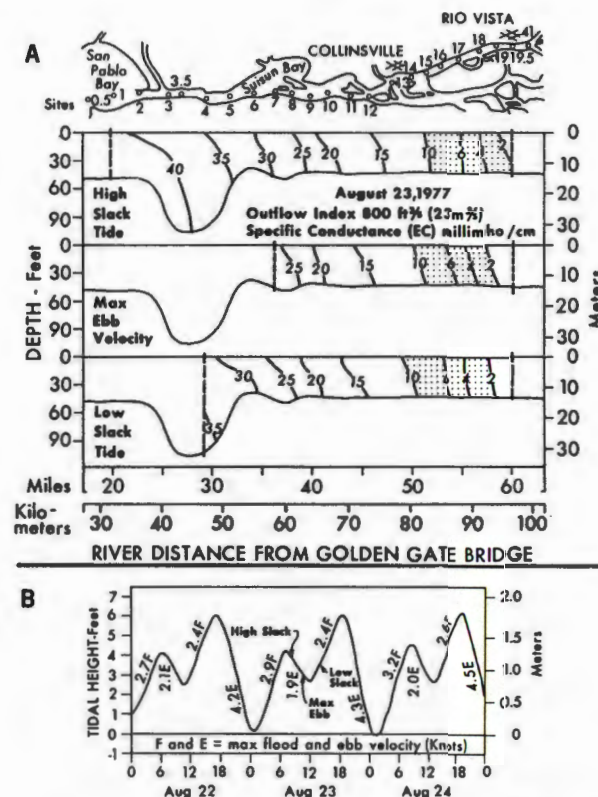
Fig. 8. A. Isoconductivity (salinity) contours measured on three consecutive tidal phases on 23 August 1977. B. Calculated Golden Gate Bridge tidal heights and maximum flood and ebb (F and E) velocities in knots.
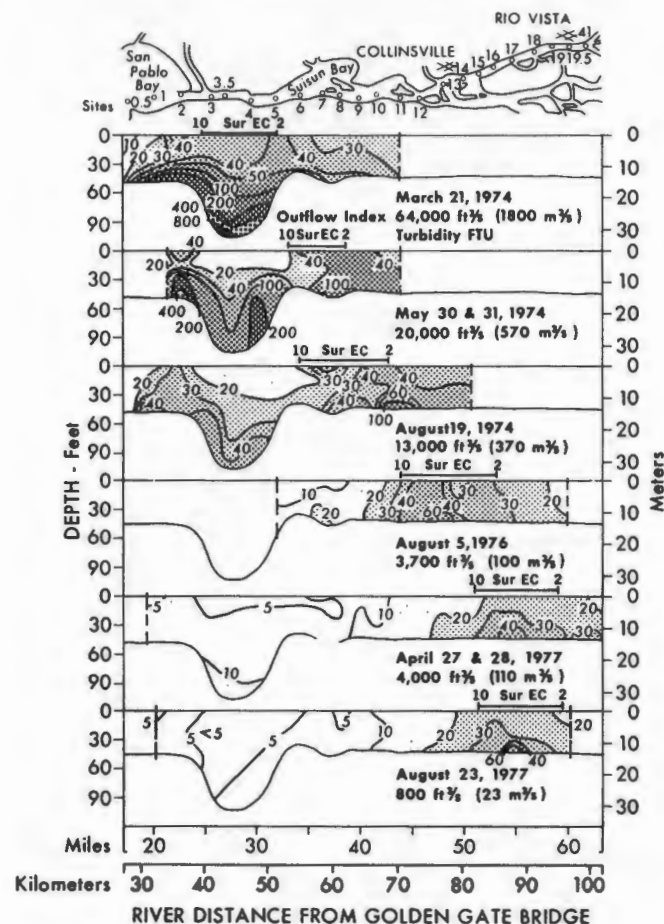
Fig. 9. Turbidity distribution relative to salinity on high slack tides at various Delta outflows.

Differences in the amount of resuspension and settling were observed between the greater and lesser flood and ebb tides (Fig. 11). The greatest resuspension of materials (between slack and maximum tidal velocity) was observed when tidal height differences and maximum velocities were high (Fig. 7) as opposed to when they were low (Fig. 8).

The maximum concentration of particulate organic nitrogen and phosphorus also typically occurred in the same general area as the maximum turbidity.

Distribution of Dissolved Materials

Dissolved constituents, of course, are not subject to entrapment by two-layered flow circulation. The concentration of nitrate+nitrite (Fig. 12), ammonia and orthophosphate generally increased with water depth and peaked downstream of the entrapment zone (see also Peterson 1979; Conomos et al. 1979).
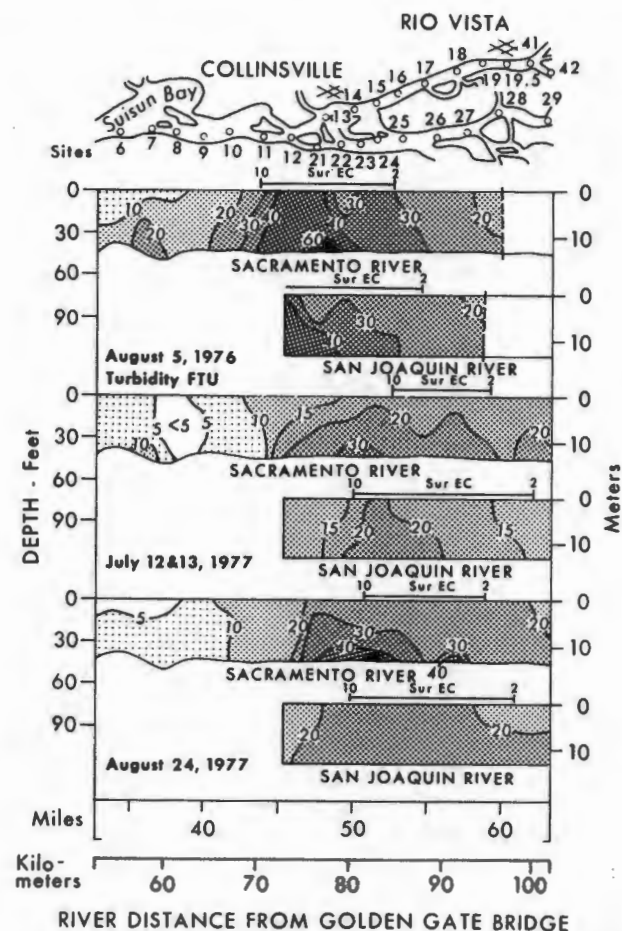
Fig. 10. Turbidity distribution in the Sacramento and San Joaquin rivers relative to salinity on high slack tides during low Delta outflow in 1976 and 1977.
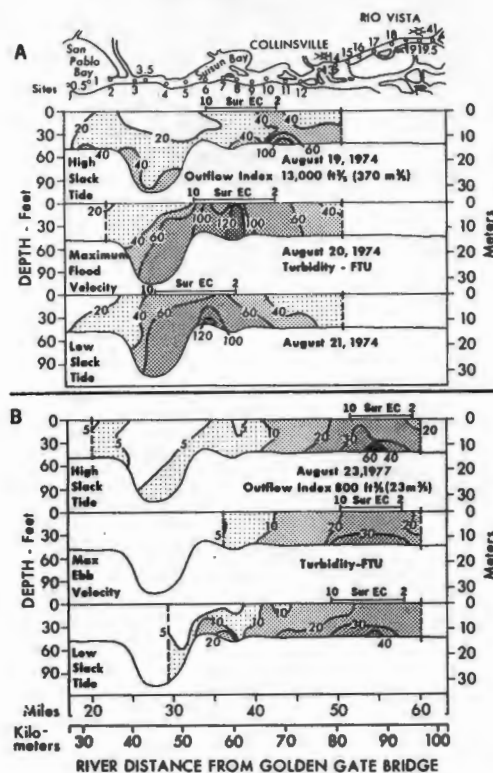
Fig. 11. A. Turbidity distribution relative to salinity measured on three consecutive days during different tidal phases in August 1974. B. Turbidity distribution relative to salinity measured on three consecutive tidal phases on 23 August 1977.

Distribution of Estuarine Biota

The same estuarine-circulation forces that influence the accumulation of suspended solids and particulate nutrients in the entrapment zone also appear to determine the distribution patterns of phytoplankton, certain zooplankton, and juvenile striped bass (young-of-the-year).

The chlorophyll *a* concentration, over a range of Delta outflows (Fig. 13), typically peaked in the entrapment zone at all Delta outflows studied. The peak concentrations in 1976 and 1977 (the two low-flow years) were the lowest ever recorded. The distribution of chlorophyll *a* and the dominant phytoplankton genera were similar throughout the study area and peaked in the 2-10 millimho·cm⁻¹ specific conductance (1 to 6 °/oo salinity) range (Fig. 14). The maximum concentration on the surface generally occurred downstream of the maximum concentration on the bottom during bloom periods (see also Ball and Arthur 1979; Conomos et al. 1979).
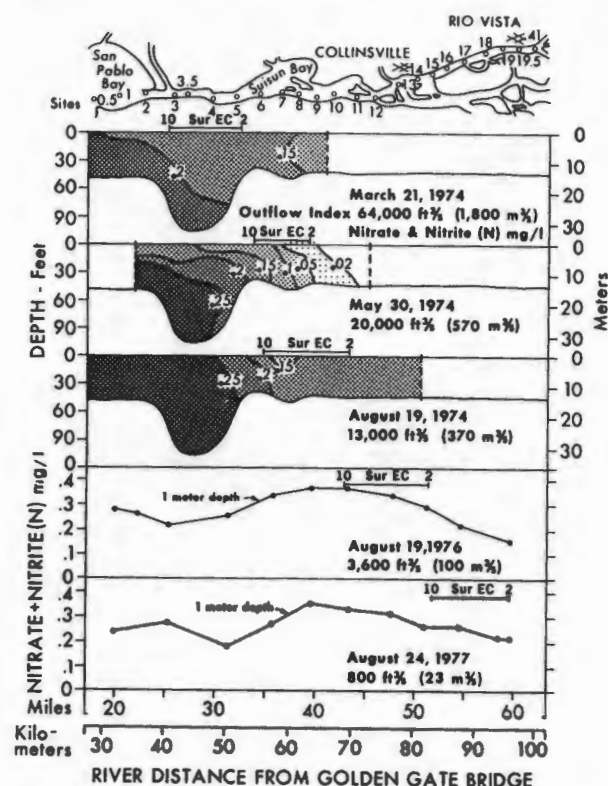
Fig. 12. Nitrate+nitrite distribution relative to salinity during high slack tides at various Delta outflows.

The various factors influencing the distribution of *Neomysis mercedis* and other zooplankton are discussed by Orsi and Knutsen (1979). The maximum abundance of *N. mercedis* and certain other zooplankton occurred in the 2-10 millimho·cm⁻¹ specific conductance (1 to 6 °/oo salinity) range. Their distribution pattern relative to salinity (Fig. 15) was similar to that of the other constituents.

The copepod distribution indicated two peaks of abundance (Fig. 16). One peak, composed of *Eurytemora hirundoides,* was centered in the approximate location of maximum suspended solids concentration. The other peak, dominated by *Acartia clausi,* was farther downstream.

The distribution of 50-mm juvenile striped bass (young-of-the-year collected in July, 1973, 1974, 1976, and 1977; Fig. 17) also appears to be related to the distribution of other suspended constituents. The peak concentrations are also related to the surface 2-10 specific conductance (1 to 6 °/oo salinity) range. Similar distribution patterns were noted for other study periods.

DISCUSSION

Entrapment of suspended materials and certain estuarine biota were evident at the entire range of outflows studied in both the Sacramento and San Joaquin rivers. Since the peak concentrations of constituents typically occurred where the surface specific conductivity was approximately in the 2-10 millimho·cm⁻¹ (1-6 °/oo salinity) range, this salinity range was selected to estimate the location of the entrapment zone.
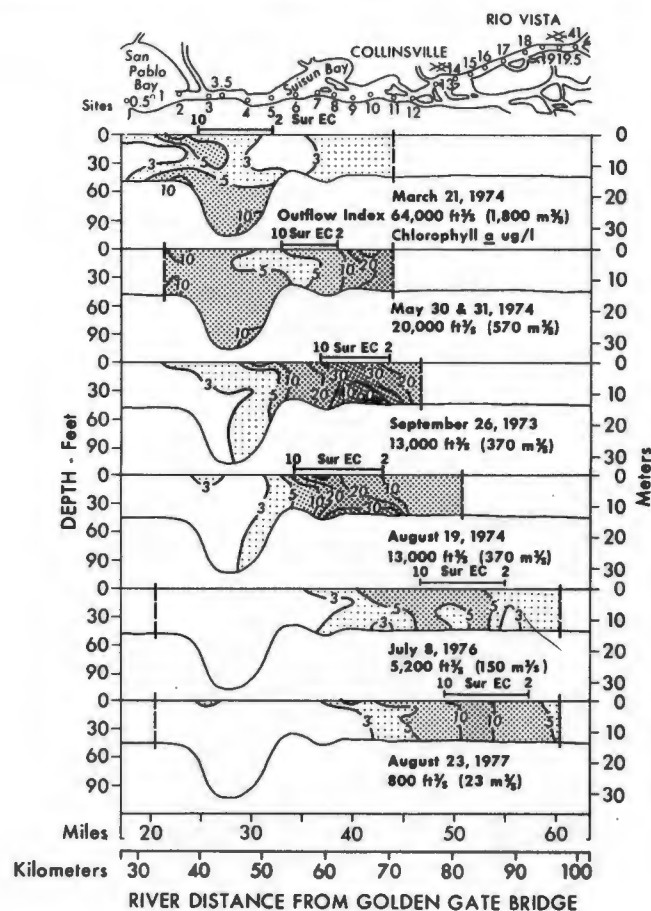

Fig. 13. Chlorophyll *a* distribution relative to salinity during high slack tides at various Delta outflows.
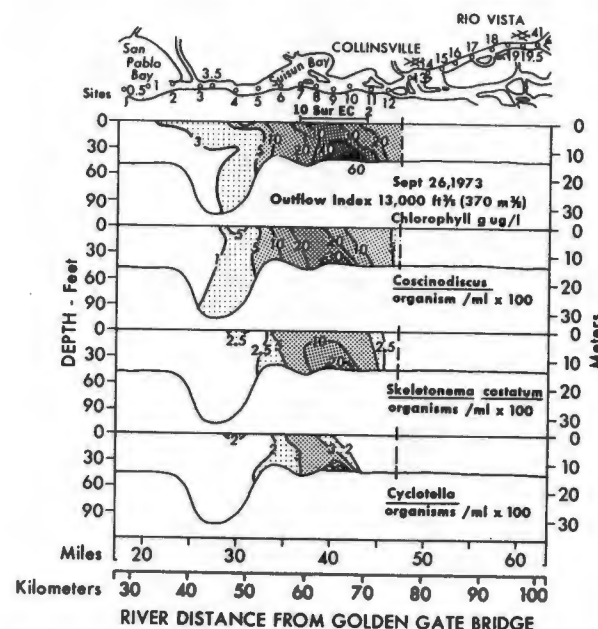
Fig. 14. Distribution of chlorophyll *a* and dominant phytoplankton genera relative to salinity during high slack tides on 26 September 1973.

Factors Influencing Suspended Materials Entrapment

Factors thought to influence the quantity of suspended materials in the entrapment zone include the riverborne suspended sediment load; flocculation, aggregation, and settling rates of particles; tidal- and wind-induced resuspension; bathymetry; dredging activities, and seasonal growth patterns of biota.

High suspended-sediment concentrations and loads to the estuary typically occur with winter floods and to a lesser extent in the late fall and early spring and increase the concentration of suspended materials observed in the entrapment zone.

In recent years, reservoir regulation of riverflows has reduced winter and spring riverflows and increased riverflows throughout the summer and early fall. Releases and drainage return flows have increased suspended sediment loads during the summer. However, flow regulation has resulted in an overall reduction of the total suspended sediment load as a result of settling that occurs in the reservoirs and sediments lost to export.

The Sacramento and San Joaquin rivers are the two main systems discharging suspended sediment to the Delta (Fig. 18). The Sacramento River (including the Yolo Bypass) contributes most (80%) of the total. The combined discharge is an estimate of the total suspended sediment load; however, during the flooding and very high outflows, suspended sediment discharge to the Delta from the Yolo Bypass may be equal to or even greater than that from the Sacramento River.
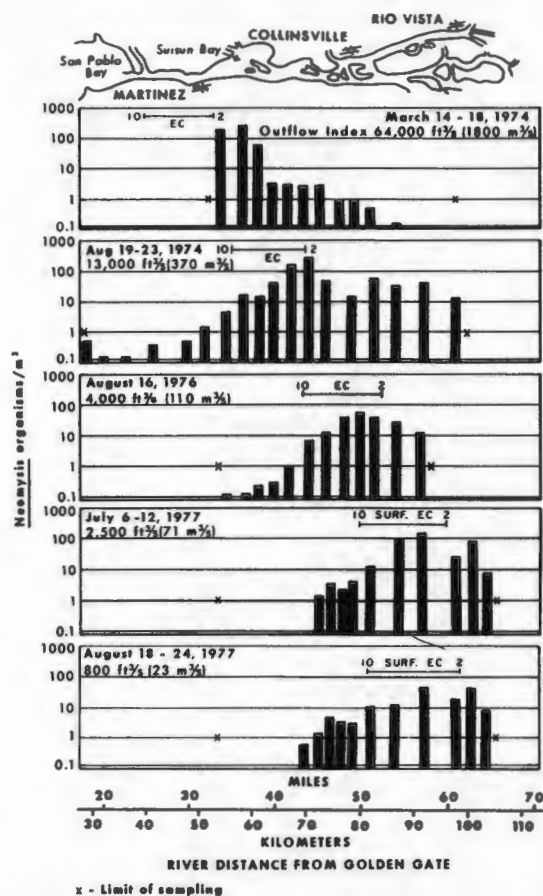
Fig. 15. *Neomysis mercedis* distribution relative to salinity on high slack tides at various Delta outflows (data collected by DFG).

Since the discharge from the Yolo Bypass is not measured, the total discharge to the Delta is often grossly underestimated.

The entrapment zone was located further seaward and with higher suspended-solids concentrations during periods of high suspended sediment discharge as compared to periods of low suspended sediment discharge (Fig. 9). These data support Postma's (1967) belief that the magnitude of the turbidity maximum (entrapment zone) is a direct function of the amount of suspended matter in the river or sea and the strength of the estuarine current.

The maximum suspended solids occurred in higher salinity water during high outflows as compared to low outflows (Fig. 9). This variation may have resulted from seasonal differences in water
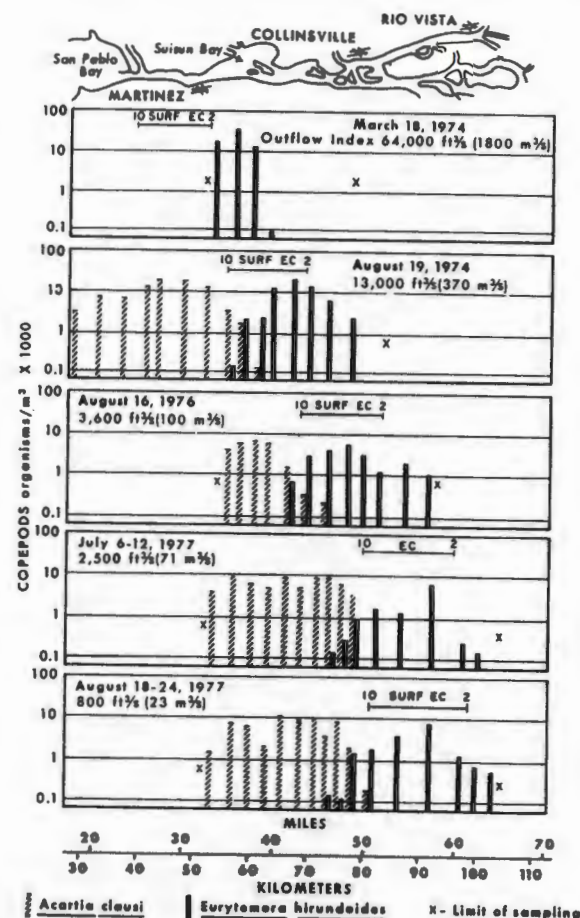
Fig. 16. Distribution of two dominant copepods (*Acartia clausi* and *Eurytemora hirundoides*) relative to salinity on high slack tides at various Delta outflows (data collected by DFG).

velocity or water temperatures. The greater net downstream velocity in the upper layer during high flows may carry the suspended materials further downstream and into more saline water before flocculation, aggregation, and settling of particles occurs. Alternatively, the settling velocity of particles could be decreased during winter by the colder water temperatures increasing the water viscosity.

There are different opinions as to what will happen to the water transparency in Suisun Bay as the amounts of riverborne sediment are decreased by future river diversions. One opinion is the water transparency is inversely correlated to the sediment load entering the estuary during any
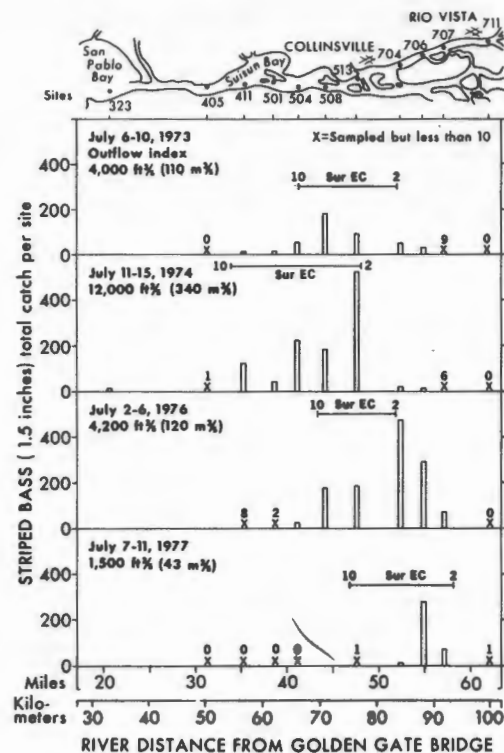
Fig. 17. Distribution of juvenile striped bass (young-of-the-year) relative to salinity on high slack tides during July 1973, 1974, 1976, and 1977 (data collected by DFG).

given year, and therefore, transparencies would increase with decreasing sediment loads. A second opinion is that winds and tidal currents along with tidal dispersion will resuspend large quantities of estuarine sediment and will maintain fairly constant transparency for many years of low river inflow.

Summer Secchi-disc measurements (made monthly during high-slack-tide from 1968-71 and twice monthly from 1972-77 by the DFG), as well as our turbidity measurements, have demonstrated a pronounced increase in water transparencies in Suisun Bay during 1976 and 1977, our two lowest outflow years. An inverse relationship between Suisun Bay water transparency and the summer Delta outflow (Fig. 19) suggests that the summer water transparency in Suisun Bay is strongly influenced by the Delta outflow. This outflow also regulates the entrapment zone location, with the zone moving upstream with the salinity intrusion and the waters of Suisun Bay becoming more transparent. Even though summer wind and tidal resuspension forces were considered to be about equal each summer, considerable transparency variation each year occurred between 1968 and 1977.
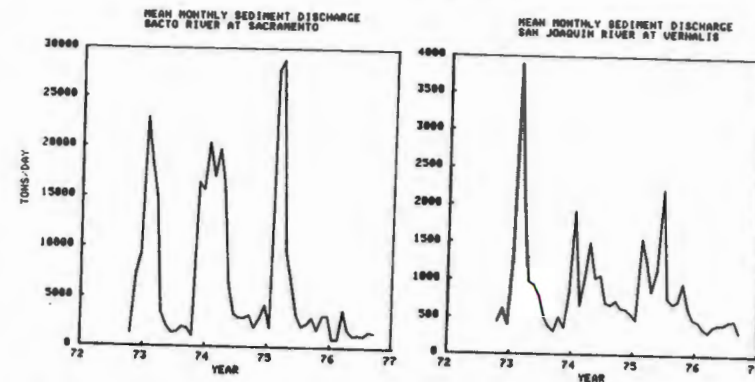
Fig. 18. Suspended sediment loads to the Delta. A. Sacramento River at Sacramento. B. San Joaquin River at Vernalis. Tons·day⁻¹ scale differs for the two rivers.

In addition to outflow, both winter and summer sediment loads, the summer inflow sediment concentration and the location of the entrapment zone relative to shallow bays have been thought to influence the summer variation in transparency between 1968 and 1977.

To evaluate the first three factors, the routine Secchi-disc measurements at 14 channel sites between Rio Vista and Martinez (when occurring in water of 2-10 millimho·cm⁻¹) were averaged
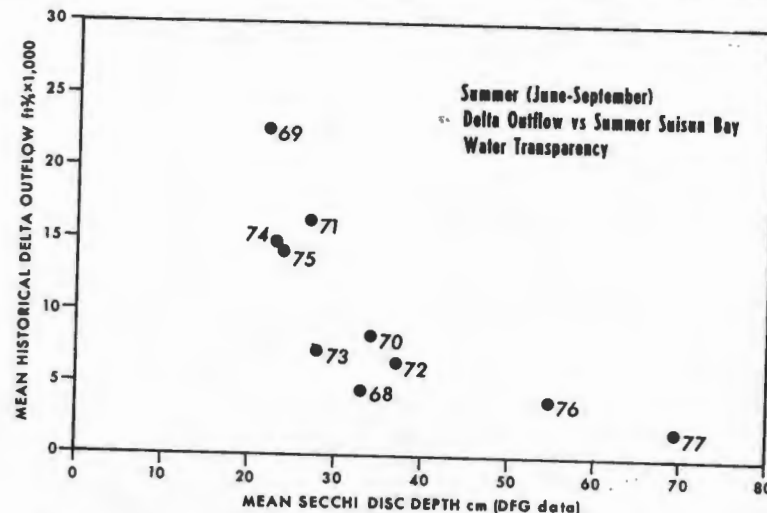

Fig. 19. Summer Suisun Bay water transparency versus summer historical Delta outflow. The 1977 outflow value was calculated as the Delta outflow index.

for each summer (June-September) and compared with the winter suspended sediment load (Fig. 20), summer suspended sediment load (Fig. 21), and summer suspended sediment concentration (Fig. 22). Although there appears to be a slight inverse relationship between the summer water transparency in the entrapment zone and the above factors, the relationships are not conclusive. Furthermore, the summer suspended sediment load as well as concentration were related to the winter load, as summer outflows that followed high outflow winters were usually also high. Since there is also so much variation in water transparency due to wind and tides one must use those evaluations with caution.
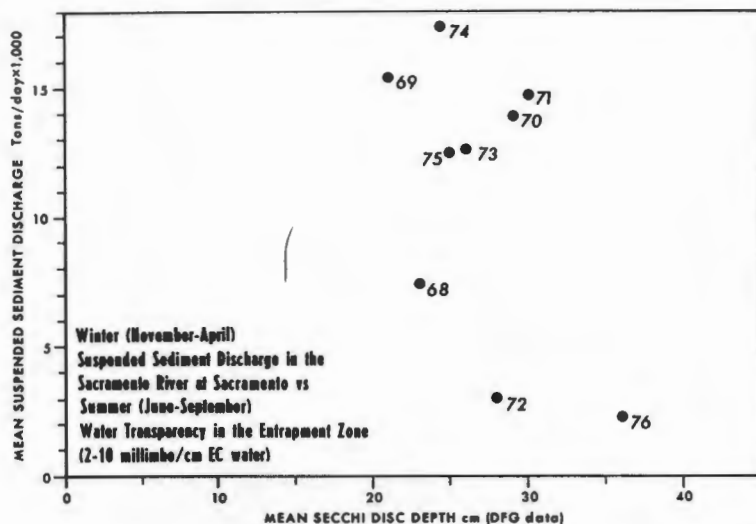
Fig. 20. Summer water transparency in the entrapment zone (2-10 millimho/cm EC range) versus winter suspended sediment load at Sacramento.

Arthur (1975), using Sacramento River water in which the salinity was adjusted with concentrated seawater brine from San Francisco Bay, demonstrated that flocculation, aggregation, and/or settling rates of suspended material increased as the specific conductance of the water samples was increased above 1 millimho·cm^{-1} (0.6 °/oo salinity) (Fig. 23).

We initiated field measurements in 1975 to obtain particle settling-rate data for verification of a suspended-solids model (O'Connor and Lung 1977) used by our study program (Arthur and Ball 1978). Particle settling rates were compared using two sampling methods. Samples from the entrapment zone were pumped into the first set of settling chambers, while the second set (special sampling-settling chambers designed by R. Krone, Univ. Calif. Davis) was lowered to the depth of sampling, the ends closed, and the settling chamber returned to the surface. Settling rates for both sets were determined by changes in turbidity at various heights in the chambers. The settling rates of particles collected by the submersible pump were several times less than those collected in settling chambers. These data suggest that the high turbulence caused by pumping disaggregates particles and imply that the particles were flocculated and/or aggregated before collection (USBR
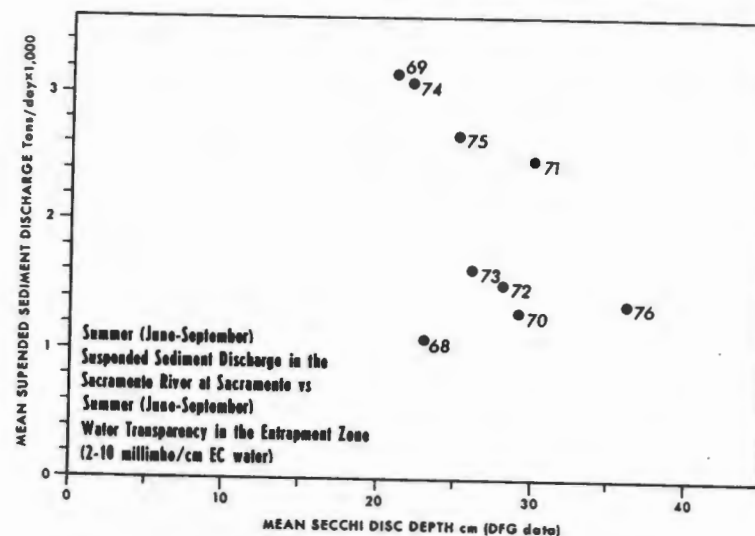
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Fig. 21. Summer water transparency in the entrapment zone (2-10 millimho/cm EC range) versus summer suspended sediment load at Sacramento.

unpublished data).

The increased surface-water transparencies with distance downstream of the entrapment zone may be caused by the removal of suspended material with settling velocities greater than the upward vertical water velocity and by increasing dilution with low-turbidity ocean water. These combined effects have not been quantified.

We do not know the extent to which flocculation increases the settling rates of suspended materials and the quantity of suspended materials in the entrapment zone. Our limited data agree with Postma (1967) who suggested that flocculation is an important factor influencing the spatial distribution and entrapment of suspended materials.

Resuspension induced by wind, tide, and dredging activities results in the continual relocation of a portion of the deposited sediments. The TSS concentrations and turbidity in the shallow areas of Suisun and San Pablo bays more than double following periods of high wind (Rumboltz et al. 1976). Increasing tidal current velocities also increase the rate of sediment resuspension, with differences in the amount of resuspension and settling observed between greater and lesser flood or ebb tides. The greatest resuspension was observed when tidal height differences and maximum velocities were highest. During calm days we have often observed highly turbid water masses a few meters in diameter to come billowing to the surface with increasing tidal-current velocities.

Dredging also tends to relocate as well as resuspend sediments. The most intense dredging occurs near Mare Island adjacent to Carquinez Strait, and when the spoils are deposited in San Pablo Bay they increase water turbidity.

The effect of estuarine circulation on suspended sediment distribution in the study area is greatly influenced by bathymetry.
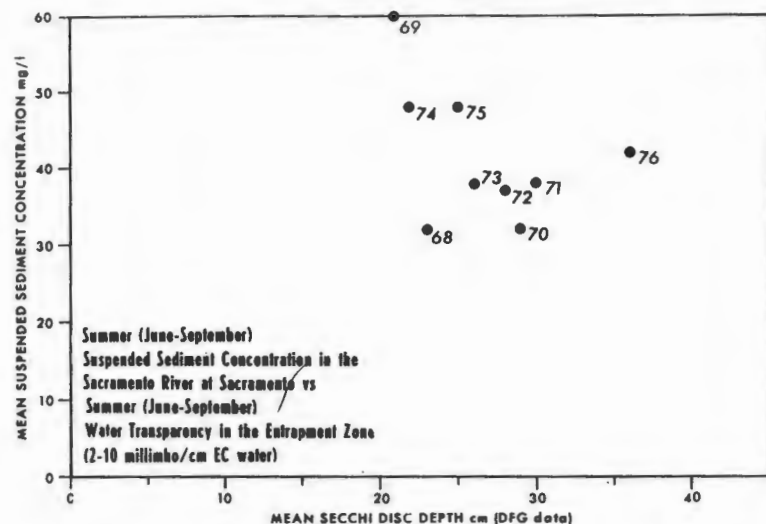
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Fig. 22. Summer water transparency in the entrapment zone (2-10 millimho/cm EC range) versus summer suspended sediment concentration at Sacramento.

Distribution of Dissolved Constituents

Dissolved constituents are not directly affected by the entrapment zone. The general increase in nitrate+nitrite (Fig. 12), ammonia, and orthophosphate with depth and distance downstream of the entrapment zone was apparently caused by numerous municipal and industrial waste discharges. Depressions in inorganic nitrogen and dissolved silica concentrations were observed when high phytoplankton standing crops accumulated in the entrapment zone (Arthur and Ball 1978; Peterson et al. 1975b; Peterson 1979).

Dissolved oxygen concentrations (at 1-m depth) in the western Delta-Suisun Bay area were always near saturation values (USBR 1972; Macy 1976) even when chlorophyll a concentrations were relatively high (50-100 $\mu g \cdot liter^{-1}$.) Oxygen concentrations one meter from the bottom were generally a few tenths of a $mg \cdot liter^{-1}$ lower than near the surface (these near-bottom oxygen measurements, although made during 1976-77, do not cover periods when high phytoplankton standing crops were present). Presumably, mixing by tidal currents and wind are adequate to maintain near-saturation levels at the present level of eutrophication (Arthur and Ball 1978).

Effects of Entrapment on the Phytoplankton Standing Crop

The location of the entrapment zone adjacent to the Honker Bay area is one of several factors which appears to greatly stimulate phytoplankton growth in the western Delta-Suisun Bay area (Arthur and Ball 1978). In the initial years of our studies (1968-75) when "typical" Delta outflows were present, the standing crop of phytoplankton tended to be highest in the years with the greatest water transparency (Ball 1977; Ball and Arthur 1979).

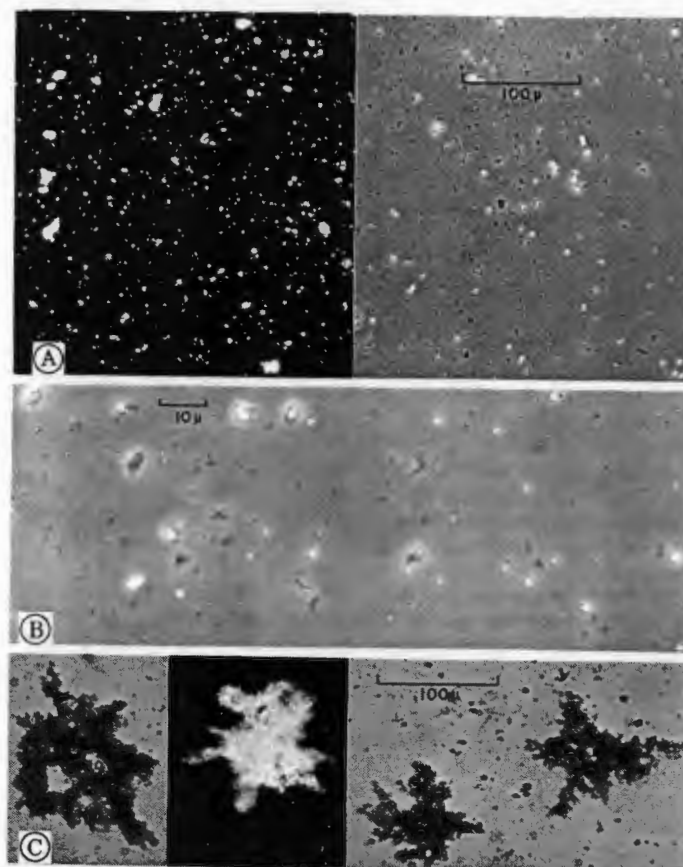The unusually low phytoplankton standing crop in Suisun Bay during the recent drought

Fig. 23. Photomicrographs illustrating laboratory-induced flocculation of suspended sediments collected from the Sacramento River during flooding conditions on 25 March 1975. A. Control (0.116 millimho/cm EC). B. Control (0.116 millimho/cm EC) (enlarged). C. After addition of concentrated sea brine (2,500 micromhos/cm EC in beaker) and 8 hr of stirring at $30 \ r \cdot min^{-1}$.

(summer of 1976 and throughout 1977) was contrary to predictions based on the 1968-75 data period. We conducted a number of field and laboratory studies during 1977 to study the low phytoplankton standing crop associated with low outflow conditions. We evaluated water transparency, water temperature, solar radiation, salinity, nutrient limitation, toxicity, parasitism, zooplankton grazing, filter feeding of benthic organisms, and the location of the entrapment zone and compared them to our previous (1968-75) observations.

The 1976-1977 data indicated that water transparencies in Suisun Bay were approximately double (Fig. 19) that of the previous years of high standing crop while solar radiation (insolation), water temperatures, and algal macro nutrients were within the normal range. Furthermore, the phytoplankton standing crop in the northern and southern Delta during 1976 and 1977 were the highest recorded although climatical conditions in these areas were similar to Suisun Bay.

A number of algal growth potential (AGP) and phytoplankton productivity studies were conducted during 1977 to determine if nutrient depletion, increased salinity, or toxicity might have been responsible for the low phytoplankton standing crop.

The AGP-test results demonstrated that the growth rates of the endemic phytoplankton tend to increase with increasing salinity and suggested that salinity intrusion into Suisun Bay during the low flow years did not directly inhibit the algal growth rates. Furthermore, because the concentration of phytoplankton in the unaltered water of the AGP tests peaked several times higher than in the field, it appeared that neither toxicity nor low concentrations of macro or micro nutrients were limiting algal growth. The primary productivity test results (DO method) in 1977 also supported this contention as the dissolved oxygen production per unit chlorophyll was equal to or higher than that of previous years.

Zooplankton concentrations were lower than normal in 1977, suggesting that grazing rates on phytoplankton should also have been lower than normal.

Although there may have been some movement of marine benthic organisms into Suisun Bay during 1976-77, it was impossible to draw any definite conclusions because there is little previous benthic data with which to compare. Comparison of 1976-77 data with future years of high phytoplankton standing crops may provide further insight into the possible significance of filter feeding of benthic organisms.

Comparison of chlorophyll a data in Suisun Bay with Delta outflows (Fig. 24a, b) shows that moderate to high chlorophyll a concentrations (above 20 μg·liter^{-1}) were present when Delta outflows ranged from 110 to 700 m^3·s^{-1}. When the outflows were below 110 m^3·s^{-1}, the standing phytoplankton crop either declined or remained low. This outflow range places the tidally averaged location of the entrapment zone at various positions adjacent to the Suisun-Honker Bay area. The highest chlorophyll concentrations were measured when the outflow varied from 140 to 200 m^3·s^{-1} in August 1970, 1972, and 1973, and September 1968 when the averaged tidal location of the entrapment zone (based on the 1-6 °/oo salinity range) was adjacent to the Suisun-Honker Bay area. In February 1976, a substantial algal bloom developed as the entrapment zone moved upstream into the Suisun-Honker Bay area earlier than normal as a result of low river flow. This bloom occurred earliest of any year. Significantly, during the bloom water temperatures were only about 12°C and the photoperiod was short (although water transparencies were high). This bloom declined in March as the water transparency decreased. A second bloom developed in April 1976 and declined as the entrapment zone moved further upstream in June 1976 with decreasing riverflow.

When the entrapment zone was upstream of Honker Bay under low (30 to 110 m^3·s^{-1}) Delta outflows (such as occurred in July and August 1966, July 1970, and June-December 1976), chlorophyll concentrations either remained low or were declining. As the 1976 drought continued into 1977 and Delta outflows remained low, the entrapment zone remained several kilometers upstream of Honker Bay for the entire year. Significantly, 1977 was the first year on record when a phytoplankton bloom did not develop in Suisun Bay. The chlorophyll a concentration in Suisun Bay was generally less than 5 μg·liter^{-1} with an occasional value of about 10 μg·liter^{-1} (see Ball and Arthur 1979).

The highest chlorophyll a concentrations (nearly 20 μg·liter^{-1}) measured west of Antioch during 1977 were in the entrapment zone (at 1 to 6 °/oo salinity) at locations above Collinsville on the Sacramento River and near Antioch on the San Joaquin River. Summer chlorophyll a
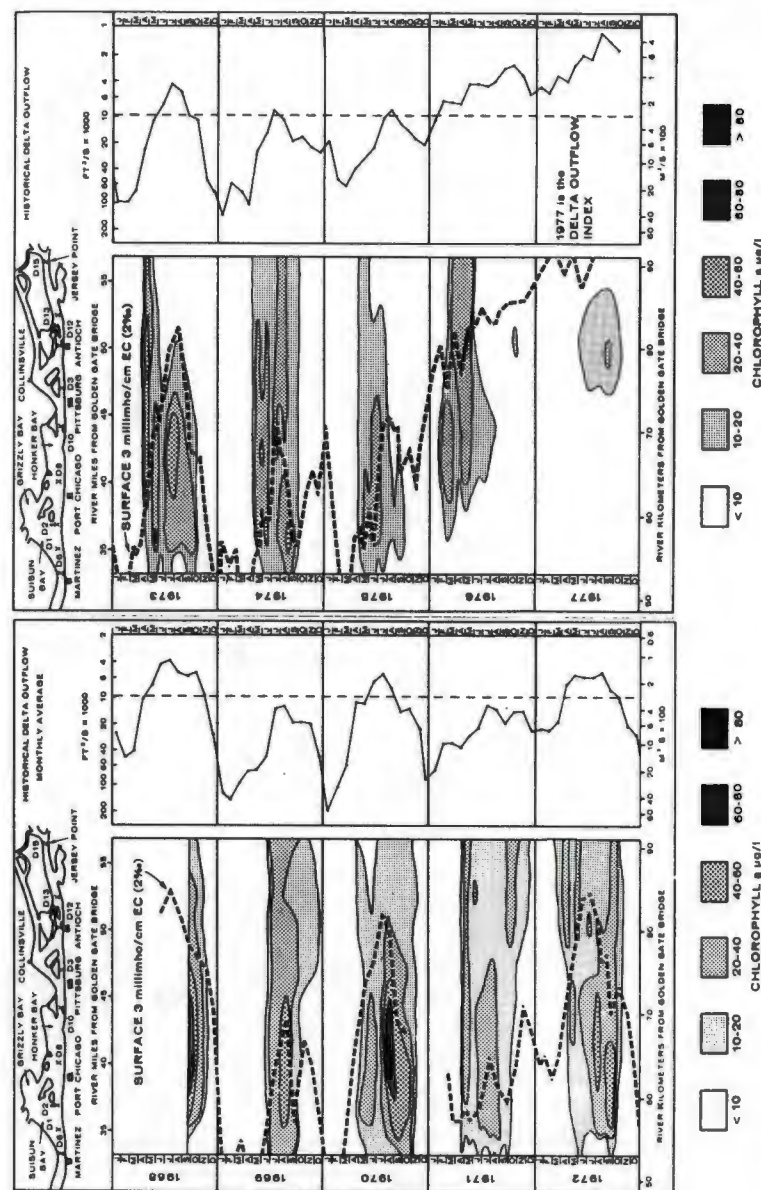
Fig. 24A and B. Chlorophyll a distribution on high slack tides from 1968-1977, between Jersey Point and Martinez, as related to salinity intrusion and Delta outflow (from Ball and Arthur 1979). (The 3 millimho/cm EC contour represents the upstream location of the entrapment zone on high slack tides.)

concentrations at the sites where the entrapment zone occurred in 1977, were in the same range as for previous years (1969-75) when the entrapment zone was farther downstream of these sites. Water transparencies at these sites in 1977 were lower than normal, suggesting that the higher phytoplankton standing crop was maintained by entrapment.

An important factor in evaluating algal growth is the residence time of algae in any given location. Whereas the residence time in any stretch of a river can be estimated by knowing the volume of water and the rate of flow, in an estuary where two-layered flow and tidal exchange occur, the residence time of algae (and other suspended materials) can either be greatly increased or reduced over that of the net downstream flow of water. The residence time of phytoplankton in two-layered flow circulation has not been directly measured. In theory, phytoplankton tend to be carried seaward if their settling velocity is less than the net vertical velocity, tend to be recirculated to and about the entrapment zone if their settling velocity is nearly equal to the net vertical velocity, or become entrapped and remain near the bottom if their settling velocity is much greater than the net vertical (upward) water velocity.

Certain algal species of the genus *Coscinodiscus* are consistently associated with the entrapment zone (Arthur and Ball 1978). These organisms have since been identified as belonging to the species *Coscinodiscus decipiens* which is synonymous with *Thalossiosira excentricus*. The organisms have thick cell walls, generally have inorganic particles attached to their exterior, and have been seen to settle rapidly in counting chambers. Their settling velocity relative to the net vertical water velocity presently being studied may provide these organisms with an ecological advantage which allows accumulation in the entrapment zone. In contrast, certain species of the genus *Chaetoceros* have cells much smaller in size which settle very slowly, have high growth rates, and at times become very dominant in the AGP test. *Chaetoceros* probably do not become dominant in the entrapment zone because their settling rates are so low; however, they often are the dominant form downstream of the entrapment zone. In addition to entrapment, the most important aspect of algal residence time related to the algal standing crop is the percent of time algal cells reside in the photic zone.

A substantial phytoplankton bloom (chlorophyll *a* >700 μg·liter^{-1} at water surface) occurred in the summer of 1977 in the McAvoy marina (south side of Honker Bay) which consisted almost entirely of *Exuviella*, a motile dinoflagellate. The intensity of the bloom gave the water a reddish-brown cast. This organism was also observed at very low concentrations in Suisun Bay during 1977. Apparently, such areas, although physically connected to the main channel, are isolated from the effects of wind, tidal current mixing and river flushing. The most logical explanation seems to be that the residence time of the algae is longer in these isolated areas than in the main channel and their mobility can maintain them near the water surface.

We do not know exactly how reduced Delta outflow and the location of the entrapment zone influence the phytoplankton standing crop in the Suisun Bay area. We offer, however, several hypotheses which when considered either singularly or in some combination may explain how the upstream movement of the zone could have caused a reduction in the Suisun Bay phytoplankton standing crop during the drought of summer 1976 and throughout 1977 (Arthur and Ball 1978):

1. *Decreased phytoplankton residence time in the Suisun Bay area when the entrapment was located upstream.* The residence time of suspended materials in rivers increases as river flow decreases. The record high phytoplankton crop in 1976 and 1977 in the northern and southern Delta (upstream of the study area) may be attributed to the increase in phytoplankton residence time resulting from lower river flows (Ball and Arthur 1979). However, in the fresh/salt-water mixing zone the water flow and mixing processes are much more complex. The longer residence time in the entrapment zone, relative to the immediate upstream and downstream areas,

may be a major factor regulating the phytoplankton standing crop. We postulate that when the entrapment zone moved upstream in 1976 and 1977, the residence time influencing the phytoplankton standing crop in Suisun Bay (both the shoals and the channel) decreased and resulted in the low phytoplankton standing crop in that area.

2. *Upstream movement of the area of maximum flocculation-aggregation-settling.* Suspended materials are in relatively low concentrations in San Francisco Bay and in the ocean. When Delta outflow were low during 1976 and 1977, the percent of ocean water nearly doubled in Suisun Bay over that of more typical years (1969-75). Furthermore, chlorophyll *a* levels during 1977 in Suisun Bay were similar to those observed in Central San Pablo Bay during the higher flow years.

We are uncertain why phytoplankton standing crops observed in the field were low in high salinity water (over 25 millimho/cm EC water) yet growth rates were highest at similar salinities in our field and laboratory growth rate tests. Perhaps the phytoplankton standing crop is characteristically low in high salinity water in the field because increased flocculation, aggregation, and/or settling of suspended particles occurs in the area downstream of the entrapment zone (the area where the net upward vertical water velocities are assumed to decrease). Phytoplankton may be affected by the increased particle settling and thus are unable to maintain themselves in the photic zone downstream of the entrapment zone. Consequently, as the entrapment zone moved upstream throughout 1976-77, greater settling rates may have occurred in Suisun Bay.

3. *Decreased phytoplankton residence time in the photic zone.* Phytoplankton are concentrated where the entrapment zone is located, with their growth rate directly proportional to the length of time they spend in the photic zone. When the entrapment zone is adjacent to the shallow bays, the average water depth present at the zone is much less than when the zone is located a dozen kilometers upstream in the more confined channels (assuming tidal exchange of the phytoplankton between the channel and the adjacent shallow bays). When the entrapment zone was located upstream in 1977, the contained phytoplankton spent less average time in the photic zone as compared to a downstream location. This hypothesis assumes complete vertical mixing of the water column.

4. *Increased vertical mixing with reduced salinity stratification.* During the low Delta outflows of 1977 the salinity stratification was less and the vertical mixing of the water column was apparently greater than during moderate to high summer outflows. The greater salinity stratification during the higher summer outflows could maintain the algae nearer the water surface and in the photic zone to a greater extent than during low outflows. Consequently, during low outflow, the reduced water stratification results in increased mixing which lowers the growth rate and standing crop of phytoplankton.

5. *Intrusion of marine benthic filter feeders.* We are uncertain whether the upstream movement of marine filter-feeding benthic organisms influenced the phytoplankton crop in 1976 and 1977.

We offer the following hypotheses that may account for the lower suspended materials concentrations observed in the entrapment zone during periods of low flow (as compared to high outflow), but do not know if or how these hypotheses may explain the low phytoplankton standing crop in Suisun Bay during 1976-77.

1. *Reduction of two-layered flow circulation.* The intensity of two-layered flow circulation should decrease as riverflow to the estuary decreases. This reduced circulation could increase the residence time of suspended materials in the entrapment zone while simultaneously reducing the quantity of suspended materials circulated through the zone. The interactions of these factors are unknown, however.

2. *Reduced aggregation and settling.* High concentrations of river-borne suspended materials increase the chances of particle aggregation in the estuary which in turn increases the settling rates of the suspended materials (R. Krone, pers. comm.). This factor may increase the quantity of material entrapped. Conversely, the quantity of suspended material entrapped decreases as the suspended-particle concentration decreases. The suspended-particle concentration entering the estuary usually varies directly with riverflow.

Factors Influencing Entrapment
of Zooplankton and Striped Bass

The results of this and other studies suggest that the maximum abundance of *Neomysis mercedis* (Fig. 15) and certain copepods (Fig. 16) relative to salinity is primarily influenced by the interaction of two-layered flow circulation on their instinctive vertical swimming behavior. Cronin and Mansueti (1971), Heubach (1969), and Siegfried et al. (1978) state that certain species of zooplankton migrate upward during the night and downward during the day. In a two-layered flow estuary this movement translates into downstream transport at night and upstream transport during the day, resulting in a roughly circular motion that retains the species near its optimal salinity range. High tidal-current velocities also result in their upstream movement (Heubach 1969; and Siegfried et al. 1978).

The different distribution patterns of *Eurytemora hirundoides* and *Acartia clausi* (Fig. 16) are attributed to differences in the optimal salinity range for these genera (Kelley 1966). The mechanism responsible could be differences in vertical swimming behavior between the two species.

We partially attributed the decrease in the total zooplankton standing crop during 1976 and 1977 to the fact that the center of the populations shifted upstream with movement of the entrapment zone into an area occupied by a smaller surface area and volume of water (Arthur and Ball 1978). The DFG has suggested that *Neomysis* and certain other zooplankton concentrations are directly related to the concentration of phytoplankton in the entrapment zone (see also Orsi and Knutson 1979). It is interesting to note that *Neomysis* (Fig. 15) and zooplankton (Fig. 16) concentrations were relatively high in March of 1974—prior to the development of a phytoplankton bloom. Unfortunately, routine sampling did not extend downstream of Martinez to characterize the distribution of both zooplankton and phytoplankton during higher Delta outflows.

The relatively high concentrations of juvenile striped bass (young-of-the-year) present in the entrapment zone may be caused by (1) the bass tending to swim to where the food supply peaks, or (2) the juvenile bass are concentrated by two-layered flow circulation in the essentially plankton stage in their early life cycles. The latter explanation seems more reasonable. Cronin and Mansueti (1971) have found that the larval forms of many Atlantic Coast fish species that spawn both in freshwater and at the entrance to estuaries are carried to the plankton-rich low salinity area (entrapment zone) where zooplankton are abundant. Stevens (1979) further discusses the factors influencing the striped bass population.

Predicting the Entrapment Zone Location

Evaluation of salinity and suspended materials data over the past 10 years indicates that the location of the entrapment zone can be predicted from salinity gradients and occurs in the upstream portion of the mixing zone where the surface specific conductance is approximately in the 2-10 millimho/cm (1 to 6 ‰ salinity) range. A plot of geographic location of this salinity range versus the DOI (at high slack tide) could be used to estimate the location of the entrapment zone at future outflows within the outflow range presented (Fig. 25). Although the overall relationship

between the location of the entrapment zone and the DOI is good, it is less precise at low outflows. This may be due to the lack of precision in calculating the DOI at low outflows, and that the location of the zone is also dependent upon both the history (variation and magnitude) of the previous outflow and on changes in tidal elevation.

Environmental Significance

The most significant environmental aspect of the entrapment zone, other than influencing the location of maximum shoaling (sediment deposition), may be that the quantity of phytoplankton and certain other estuarine biota are enhanced when the zone is located in upper Suisun Bay. The lowest levels of phytoplankton and certain zooplankton recorded in the Suisun Bay area occurred during 1976 and 1977 when the Delta outflow was low and the entrapment zone was located several kilometers upstream of Honker Bay. However, we do not yet know the significance of a long-term low Delta outflow on total estuarine productivity.
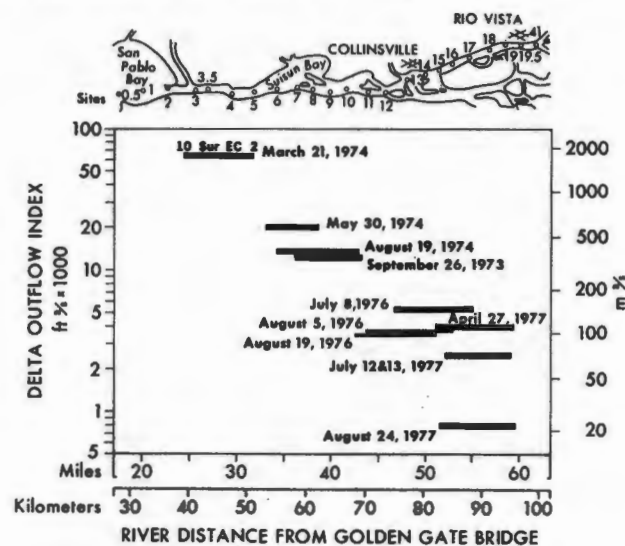

Fig. 25. Estimated high slack tide locations of the entrapment zone, based on the 2-10 millimho/cm EC (1-6 ‰) range at various Delta outflows.

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SOURCES AND SINKS OF BIOLOGICALLY REACTIVE OXYGEN, CARBON, NITROGEN, AND SILICA IN NORTHERN SAN FRANCISCO BAY

DAVID H. PETERSON

U.S. Geological Survey, 345 Middlefield Road, Menlo Park, CA 94025

The distributions of biologically reactive dissolved oxygen, carbon, nitrogen, and silicon (OCNSi) in the main channels of northern San Francisco Bay appear to be related to winter and summer variations in the dynamics of the estuary. At moderate or higher (>500 m^3·s^{-1}) river flow, OCSi distributions in the estuary frequently are nearly conservative. Thus, during high river discharge periods, the relative effects of additional estuarine sources and sinks (waste inputs, phytoplankton production and remineralization, or atmospheric- and benthic-exchange processes) appear to be minimal. At such river flows replacement time for estuarine water is on the order of weeks, whereas the OCNSi replacement (turnover) times due to additional sources and sinks are longer. The turnover time of NH$_3$-N, however, is shorter. The river and ocean are probably not major sources of NH$_3$ to the estuary.

Marked departures from near-conservative OCNSi distributions occur during low river flow (<200 m^3·s^{-1}) when the magnitudes of the local sources and sinks may exceed river and ocean inputs. As an overview, however, several processes seem to control these distributions at comparable rates and no one factor dominates: dissolved oxygen is typically 5 to 10% below saturation concentrations; dissolved carbon dioxide is 150-200% above saturation concentrations and in approximate balance with oxygen consumption; phytoplankton production keeps pace with waste inputs of nitrogen; and dissolved silica is maintained above concentrations that would be limiting for phytoplankton growth.

Knowledge of estuarine hydrodynamics and of the appropriate sources and sinks is needed to predict micronutrient and dissolved-gas distributions in an estuary. This chapter presents a series of inferences about the processes which control oxygen, carbon, nitrogen, and silica (OCNSi), based on their observed distributions. These elements were studied because an understanding of their behavior is basic to our knowledge of natural water chemistry in an estuary. The discussion is limited to the northern part of the San Francisco Bay estuary between the Golden Gate and Rio Vista herein termed North Bay (Fig. 1). The southern reach (South Bay), from the Golden Gate to San Jose, has only a small freshwater inflow and is not discussed here (see Conomos 1979; Conomos et al. 1979).

Under certain assumptions and with appropriate rate measurements we can estimate sources and sinks of these elements throughout North Bay. To some extent the magnitudes and positions of these sources and sinks are, of course, always shifting and changing. Thus, to put the sources and sinks into perspective and to illustrate how they might interrelate with one another, a simple conceptual model of North Bay is used. The model, which has fixed dimensions and receives seasonally varying runoff and insolation, is used for discussion purposes with the understanding it can provide only gross budgets.

State of California
The Resources Agency

DEPARTMENT OF FISH AND GAME

REPORT TO THE FISH AND GAME COMMISSION:

A STATUS REVIEW OF THE
DELTA SMELT (HYPOMESUS TRANSPACIFICUS)
IN CALIFORNIA

Prepared by

Donald E. Stevens
Fisheries Management Supervisor

Lee W. Miller
Associate Fishery Biologist

and

Betsy C. Bolster
Associate Fishery Biologist

Approved by

Harold K. Chadwick, Program Manager
Bay-Delta Project
and
Robert R. Rawstron, Chief
Inland Fisheries Division

August 1990

Candidate Species Status Report 90 - 2

TABLE OF CONTENTS

Report to the Fish and Game Commission:

A Status Review of the

Delta Smelt (<u>Hypomesus</u> <u>transpacificus</u>)

in California[1]

EXECUTIVE SUMMARY

This report was prepared in response to a petition received by
the Fish and Game Commission from Dr. Peter B. Moyle of the
University of California at Davis to list the Delta smelt
(<u>Hypomesus</u> <u>transpacificus</u>) as an Endangered Species under the
authority of the California Endangered Species Act (Fish and Game
Code Sections 2050 et seq.).

On August 23, 1989, pursuant to the Section 2074.2 of the
California Endangered Species Act (CESA), the Commission
determined that the petition contained sufficient information to
indicate that the petitioned action may be warranted. Pursuant
to Section 2074.6 of CESA, the Department undertook a review of
this petition. Based on the best scientific information
available on the Delta smelt, the Department has evaluated
whether, in fact, the petitioned action should be taken.
Information and comments on the petitioned action and the Delta

1/ Prepared August 1990.

iii

smelt were solicited from interested parties, management
agencies, and the scientific community.

This report presents the results of our review and analysis.

Findings

The Delta smelt is a small fish endemic to the Sacramento-San
Joaquin Estuary. Delta smelt are euryhaline and much of the year
are typically most abundant in the entrapment zone, where
incoming saltwater and outflowing freshwater mix. This species
feeds exclusively on zooplankton, spawns in freshwater, and
usually only lives for one year.

Information from six different data sets all indicate that the
population of Delta smelt has declined. The best measures, based
on the summer townet and fall midwater trawl surveys, indicate
that abundance of this species has been consistently low since
1983. Based on the midwater trawl survey, the average population
since 1983 has been only about one-fifth of the average
population level from 1967 to 1982, and one-tenth of the peak
level in 1980.

Conclusions

Although the petitioner requested that the species be listed as
endangered, the Department finds that the Delta smelt should be

listed as a threatened species, based on Section 670.1(b) of Title 14 of the California Code of Regulations and Section 2072.3 of the Fish and Game Code. The Department's findings are based on the following:

1.   The recent decline in the copepod, _Eurytemora affinis_, a major diet component of the Delta smelt, must be considered as a potential threat to the smelt's recovery unless other food resources compensate or this copepod recovers to its former abundance.

2.   Although spawning stock abundance may not have been an important factor in Delta smelt year class success in the past, present or future low stock levels may inhibit the potential for population recovery. The relatively low fecundity of this species and its planktonic larvae, which undoubtedly incur high rates of mortality, indicate that year class success of the Delta smelt must depend on reproduction by fairly large numbers of fish.

3.   The relationship between Delta smelt abundance and water diversions is not clear. Delta smelt are ecologically similar to young striped bass which have been severely impacted by water diversions. Whether or not water diversions are directly responsible for the Delta smelt

population decline, their drain on the population may be a significant factor inhibiting recovery.

4.   Although there is no direct evidence of Delta smelt suffering direct mortality or stress from toxic substances, such substances cannot be eliminated as having adverse effects on the population.

5.   There is no evidence that Delta outflow has had major effects on Delta smelt abundance.

6.   No research has been done to determine if the wagasaki, a closely related species introduced into several reservoirs in the Delta drainage, hybridizes with or competes directly with the Delta smelt.

7.   A number of exotic fish and invertebrate species have been introduced into the Sacramento-San Joaquin Estuary. Although none of these species can be directly linked to the decline in Delta smelt, their presence may inhibit the smelt's recovery.

8.   Diseases and parasites of Delta smelt have never been studied; thus, there is no evidence concerning their role in the population decline. Should they be important, they

could prevent the recovery of Delta smelt from current low
population levels.

9. Although competition and predation cannot be ruled out as
    threats to Delta smelt, the available evidence suggest that
    they are not a major threat. In fact, several potential
    competitors or predators also show signs of population
    erosion approximately coinciding with or preceding the
    decline of Delta smelt.

10. The Delta smelt population trend, certain life history
    attributes, and environmental threats tend to support
    listing. The scientific information is insufficient,
    however, to determine whether the population is low enough
    that it is in imminent danger of extinction. This is a
    complicated scientific determination, and no study which
    might be implemented will provide a conclusive answer in the
    next few years. Meanwhile, the population might become
    extinct. The most prudent action, therefore, is to list the
    Delta smelt as a threatened species.

Recommendations

Listing:

1. The Commission should find that the Delta smelt is a threatened species.

2. The Commission should publish notice of its intent to amend Title 14 CCR 670.5 to add the Delta smelt (_Hypomesus transpacificus_) to its list of Threatened and Endangered Species.

Management and recovery objectives:

1. Improve species identification and fish handling procedures at the existing State and Federal Water Project diversions from the Delta. Such actions could reduce present entrainment losses to these major diversions.

2. Modify pumping strategies at the State and Federal Water project diversions to reduce entrainment losses during periods when delta smelt are most abundant.

3. Increase spring and summer delta outflows to maintain the entrapment zone and major delta smelt nursery in the Suisun

Bay region where food supplies are greater that in the Delta and exposure to diversions is minimal.

4. Support regulations restricting ship ballast water discharges to eliminate or minimize new introductions of potentially harmful exotic species. S 2244 and HR 4214 currently being considered by the U.S. Congress would create such regulations.

5. Evaluate losses to agricultural diversions in the Delta. Screening these diversions probably would reduce entrainment and losses to local crop irrigation.

6. Remove water project diversions from the Delta. Moving the diversion intakes to the Sacramento River upstream from the major nursery area would do this and also provide benefits to other species which formerly made more use of the Delta.

7. Consider developing pond culture techniques for the purpose of creating "refuge" populations.

Public Responses

During the twelve month review period, the Department contacted a number of affected and interested parties, invited comment on the petition and our draft status review, and requested any

additional scientific information that may be available. A copy
of the Public Notice and a list of parties contacted are
contained in Appendix A. A summary of comments on the draft
status review is in Appendix B. Scientific comments will be
addressed as part of the regulatory proceedings should the
Commission find that the petition warrants action.

LIST OF TABLES

LIST OF FIGURES

Report to the Fish and Game Commission:

A Status Review of the

Delta Smelt (_Hypomesus_ _transpacificus_)

in California[1]

INTRODUCTION

Petition History

On June 13, 1989, the Fish and Game Commission (Commission)
received a petition from Dr. Peter B. Moyle of the University of
California at Davis, requesting State listing of the Delta smelt
(_Hypomesus_ _transpacificus_) as an Endangered Species. The
Department of Fish and Game (Department) reviewed the petition
and recommended to the Commission that they accept it as complete
pursuant to Sections 2072.3 and 2073.5 in the California
Endangered Species Act (Fish and Game Code Sections 2050 et seq.)
and that the petitioned action may be warranted. On August 29,
1989, the Commission accepted the Department's recommendation and
designated the Delta smelt as a Candidate Species as provided for
in Section 2074.2 of the California Endangered Species Act
(CESA). That action initiated a twelve-month review period,

1/ Prepared August 1990

1

pursuant to Section 2074.6 of CESA, within which the Department must review the best scientific information available on the Delta smelt and provide a written report to the Commission indicating whether the petition is warranted.

Department Review

This report contains the results of the Department's review, and a recommendation to the Commission, based on the best scientific information available, whether or not the petitioned action is warranted. It also identifies the habitat that may be essential to the continued existence of the species and suggests management activities and other recommendations for the recovery of the Delta smelt.

During the twelve month review period, the Department contacted affected and interested parties, invited comment on the petition and our draft status review, and requested any additional scientific information that may be available, as required under Section 2074.4, Fish and Game Code. A copy of the Public Notice and a list of parties contacted are contained in Appendix A. A summary of comments on the draft status review is in Appendix B. Scientific comments will be addressed as part of the regulatory

2

proceedings should the Commission find that the petition warrants
action.

<center>LIFE HISTORY</center>

Description

The Delta smelt is a small, slender-bodied fish, with a typical
adult size of 55-70 mm (standard length), although some may reach
130 mm. This fish has a small, flexible mouth with a maxilla
(upper jaw bone) which does not extend past the middle of the
eye.   When pressed against the body, the pectoral fins reach
less than two-thirds of the way to the pelvic fin bases. The
upper and lower jaws contain small, pointed teeth. Live Delta
smelt have a steely blue sheen on the sides and appear to be
almost translucent (Moyle 1976).   Delta smelt, like other
members of the family Osmeridae, have an adipose fin.
Additional, more detailed descriptive information can be found in
Moyle (1976).

Taxonomy

The confusing taxonomy of this species is described in Moyle
(1976). The Delta smelt was once thought to be a population of
the widely distributed pond smelt, Hypomesus olidus. The two

<center>3</center>

were recognized as distinct species by Hamada (1961), who renamed the Delta smelt H. sakhalinus and retained the name H. olidus for pond smelt. It was later determined, however, that H. olidus does not occur in California waters, and McAllister (1963) redescribed the Delta smelt as H. transpacificus, with Japanese and California subspecies, H. t. nipponensis and H. t. transpacificus, respectively. Subsequent work has shown that these two subspecies should be recognized as species, with the Delta smelt being H. transpacificus and the Japanese fish (wagasaki) being H. nipponensis (Moyle 1980).

Range

The delta smelt occurs only in the Sacramento-San Joaquin Estuary.

Diet

Delta smelt feed exclusively on zooplankton. Department biologists examined gut contents of two 8 mm and 9 mm delta smelt larvae captured in 1988 which had eaten harpacticoid copepods, calanoid copepods and copepod nauplii. The diet of 20-mm to 40-mm-long juveniles collected by the Department in 1974 was comprised mainly of calanoid copepods, especially Eurytemora affinis, which was the dominant food (Table 1). There was no evidence of a major shift in diet as the smelt grew larger.

4

Table 1.   Items in the diet of delta smelt collected from the townet survey
at station 519 on June 28 and July 13, 1974.

Length group (mm)	Total fish	Number w/food	Cyclopidae	Eurytemora	Diaptomus	Harpacticoid copepod	Neomysis	Other copepod
20-24	2	1		2				
25-29	18	17		117	1	1		8
30-34	18	17	2	585			1	45
35-39	12	12	0	220			1	34

Moyle and Herbold (MS) examined the diet of delta smelt from 15
samples collected at various times from 1972 to 1974 and for two
fall samples collected in 1988. They found copepods to be the
dominant diet item and the opossum shrimp, _Neomysis mercedis_, was
second. _E. affinis_ was the primary copepod in stomachs in the
1972-1974 sample. _Pseudodiaptomus forbesi_, an accidentally
introduced exotic copepod which first became abundant in spring
1988, was an important diet item that year. The amphipod,
Corophium sp, and two cladocerans, _Bosmina_ sp. and _Daphnia_ sp.,
were also eaten.

Reproduction and Growth

Spawning occurs in freshwater at temperatures of 7-15°C (Wang
1986). It generally takes place from February through June,
probably mostly in the dead end sloughs (Radtke 1966) and shallow
edge-waters of the channels of the Delta (Wang 1986) and the
Sacramento River. Catches of young delta smelt, 20-30 mm in
length, during salmon seine surveys in May document the
occurrence of spawning in the Sacramento River (Table 2). Some
spawning has also been recorded in Montezuma Slough, near Suisun
Bay (Radtke 1966, Wang 1986). Each female deposits from 1400 to
2900 demersal, adhesive eggs on substrates such as rock, gravel,
tree roots, and submerged vegetation (Moyle 1976; Wang 1986;
Moyle and Herbold, MS). Eggs probably hatch in 12-14 days if

6

Table 2. Catch per haul (C/H) and mean fork length in millimeters (FL)
of delta smelt at Sacramento River beach seine sites in 1978.
Number of seine hauls in parentheses.

Site	Feb C/H	FL	Mar C/H	FL	Apr C/H	FL	May C/H	FL	June C/H	FL
Isleton	(0)		1.3 (3)	69	0.0 (1)		2.0 (1)	22	(0)	
Ryde	(0)		1.0 (2)	46	1.2 (4)	75	13.3 (3)	24	(0)	
Clarksburg	(0)		0.0 (5)		5.8 (4)	68	70.7 (3)	26	(0)	
Garcia Bend	0.0 (2)		1.5 (4)	66	0.2 (4)	71	5.7 (3)	24	(0)	
Mouth American River	0.0 (2)		0.0 (5)		0.0 (3)		0.2 (4)	68	0.0 (1)	

7

developmental rates are similar to those of the closely related wagasaki (Wales 1962).

After hatching, larvae float to the surface (Moyle 1976) and many are carried by currents downstream to the mixing (entrapment) zone (see "Distribution and Essential Habitat"). Growth is rapid; juvenile smelt are 40-50 mm long by early August (Erkkila et al. 1950, Ganssle 1966, Radtke 1966). Adult lengths are reached by the time they are 6 to 9 months old (Moyle 1976). Thereafter, they only grow another 3-9 mm, presumably because most energy is being channeled into the development of gonads (Erkkila et al. 1950, Radtke 1966).

Most Delta smelt die after spawning, although a few may survive to be 2 years old. There is evidence that almost total reproductive failure can occur in some years. Erkkila et al. (1950), for example, collected no young-of-the-year smelt in their second year of sampling, although their previous year's data suggested that large numbers should have been present.

DISTRIBUTION AND ESSENTIAL HABITAT

Delta smelt are euryhaline, and much of the year are typically most abundant in the entrapment zone (Arthur and Ball 1979) where

incoming saltwater and outflowing freshwater mix (Tables 3, 4,
and 5). This mixing effect allows organisms which swim poorly,
such as zooplankton and larval fish, to remain in the entrapment
zone rather than being flushed out to sea. Hence, delta smelt
spend their life from the larval period to pre-spawning adulthood
in the Delta and brackish areas downstream, particularly the
Suisun Bay region (Ganssle 1966, Radtke 1966, Moyle and Herbold
1989). Surveys by the San Francisco Bay - Outflow Study, which
has sampled fish in the Estuary from San Francisco Bay to the
western Delta since 1980, indicate that delta smelt thin out in
San Pablo Bay and are virtually non-existent in San Francisco Bay
(Table 3).

Summer townet and fall midwater trawl surveys (pages 17 to 23),
conducted by the Department for young striped bass (Morone
saxatilis), indicate delta smelt are most frequently caught where
specific conductance ranges from 500 to 8000 microsiemens (Tables
3, 4 and 5). These surveys also demonstrate that the
geographical distribution of delta smelt during summer and fall
is strongly influenced by delta outflow. As flows increase and
saltwater is repelled, more of the population occurs in Suisun
and San Pablo bays and less occurs in the Delta (Figures 1 and
2).

Table 3. San Francisco Bay - Outflow study catch of delta smelt by month and area,
1980-1988. Number of sampling sites in parentheses.

Area	Month												
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
San Francisco Bay (16)	0	0	0	0	0	0	0	0	0	0	0	0	0
San Pablo Bay (8)	4	5	29	1	0	1	0	0	0	54	0	1	95
Carquinez Strait and Western Suisun Bay (6)	61	46	86	37	5	55	70	94	71	36	9	38	608
Eastern Suisun Bay (3)	18	24	15	10	5	8	16	37	54	68	40	12	307
Western Delta (2)	30	13	15	5	2	20	12	23	55	12	33	32	252
Total	113	88	145	53	12	84	98	154	180	170	82	83	1262

10

Table 4. Summer townet survey catch frequencies for delta smelt by specific conductance
(EC) ranges, 1969-1988. 1/

Numbers of smelt per catch

EC (microsiemens)	0	1-4	5-9	10-14	15-19	20-49	50-99	>100	Total Samples	Number Catches >0	Percent with smelt
No Data	9	4	3	1	0	1	1	0	19	10	52.6
1-499	541	170	52	17	10	36	16	14	856	315	36.8
500-999	105	51	13	16	7	13	14	10	229	124	54.1
1000-1999	38	31	15	10	8	17.	9	10	138	100	72.4
2000-3999	34	41	15	11	8	22	9	8	148	114	77.0
4000-5999	31	30	11	6	4	6	8	8	104	73	70.0
6000-7999	22	21	9	7	3	11	5	1	79	57	72.1
>8000	338	96	32	14	7	17	14	3	521	183	35.1
Total	1118	444	150	82	47	123	76	54	2094	976	46.6

1/ EC was not measured prior to 1969 even though the survey
started in 1959.

11

Table 5. Fall midwater trawl catch frequencies for delta smelt by specific conductance
(EC) ranges, 1967-1988.

Numbers of smelt per catch

EC (microsiemens)	0	1-4	5-9	10-14	15-19	20-49	>50	Total Samples	Number Catches >0	Percent catch with smelt
No Data	9	0	0	0	0	0	0	9	0	0
1-499	1756	604	103	30	16	27	4	2540	784	30.8
500-999	311	137	35	21	7	12	5	528	217	41.1
1000-1999	224	128	43	18	10	18	2	443	219	49.4
2000-3999	269	141	44	30	9	14	5	512	243	47.4
4000-5999	244	97	45	9	10	12	1	418	174	46.1
6000-7999	202	67	23	10	5	9	1	317	115	36.3
>8000	4547	173	24	9	9	11	4	4777	230	4.8
Total	7562	1347	317	127	66	103	22	9544	1982	20.7

12

CDFG TOWNET SURVEY – DELTA SMELT DISTRIBUTION
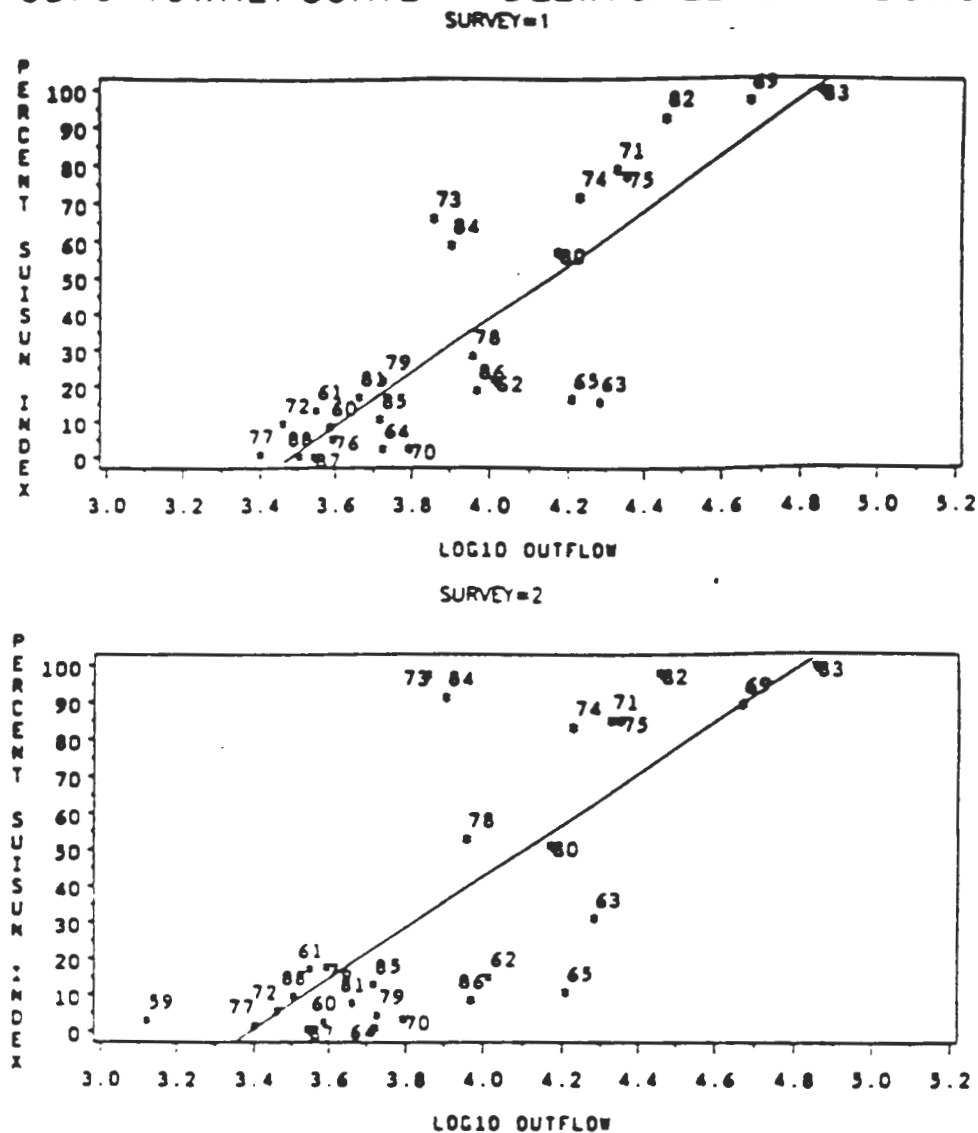
Figure 1. Relationship between the portion of the delta smelt population occurring west of the delta and log delta outflow during the survey period. Data are from the summer townet survey. For arcsine transformed percentages, $R^2 = 0.74$ for survey 1 and $R^2 = 0.55$ for survey 2.

Figure 2. Relationship between the portion of the delta smelt population occurring west of the delta and log delta outflow during the survey month. Data are for the fall midwater trawl survey. For arcsine transformed percentages, R^2= .640 for September, .763 for October, .708 for November and .336 for December.

14

In late winter and spring, as the spawning period approaches, adult delta smelt disperse widely into freshwater, as far upstream in the Delta as Mossdale on the San Joaquin River (Radtke 1966) and (as indicated by trawling and seining during recent chinook salmon, Oncorhynchus tshawytscha, surveys) the mouth of the American River on the Sacramento River (Tables 2 and 6).

Delta smelt live principally in the upper portion of the water column. During a 1963-1964 survey of delta fish populations a 10 foot by 10 foot surface trawl captured 1960 delta smelt while a 15 foot by 5 foot otter trawl only captured 461 delta smelt. These results were obtained despite the otter trawl constituting 60 percent of this surveys effort of about 1800 tows (Radtke 1966, Turner 1966).

<div align="center">ABUNDANCE</div>

Information from five Interagency Ecological Study Program monitoring programs and one University of California program was summarized to evaluate recent trends in delta smelt abundance:

1.   the summer townet survey for young striped bass,
2.   the fall midwater trawl survey for young striped bass,
3.   the San Francisco Bay-Outflow Study's monthly midwater trawl survey,

Table 6. Catch of Delta Smelt by midwater trawl in the Sacramento River
          at Clarksburg, 1976-1981. This site has not been sampled in
          more recent years. N/M means not measured. Lengths in mm.

Year	May Catch	May Mean Length	May No. Tows	June Catch	June Mean Length	June No. Tows	July Catch	July Mean Length	July No. Tows
1976	218	79	147	69	80	342	7	84	94
1977	242	N/M	443	117	N/M	550	0		95
1978			0	8	82	127			0
1979			0	15	78	100			0
1980			0	6	84	240			0
1981			0	29	80	139			0

4. the seine and midwater trawl monitoring of young chinook salmon,

5. "salvage" of fish at the State and Federal water project fish screens in the south Delta, and

6. the University of California, Davis, Suisun Marsh fish survey.

While these data sets all provide information on delta smelt abundance at the time and location of sampling, each has inherent strengths and weaknesses in depicting the true population trend. These strengths and weaknesses are discussed as appropriate in the subsequent sections of this report.

Summer Townet Survey

The Department has conducted semi-monthly tow net surveys in the Delta and Suisun Bay, from late June to early August, each year since 1959 (except 1966) to index the abundance of young striped bass. On each survey run, three tows are made at each of about 30 sites from San Pablo Bay upstream through most of the Delta (Figure 3). Each survey run takes 5 days, and runs are made at 2-week intervals until the young bass average 38 mm (1.5 inches) in length. The number of runs has varied from two to five annually . The sampling gear and methods are described in detail by Calhoun (1953), Chadwick (1964), Turner and Chadwick (1972) and Stevens (1977). Catches of delta smelt are a by-product of
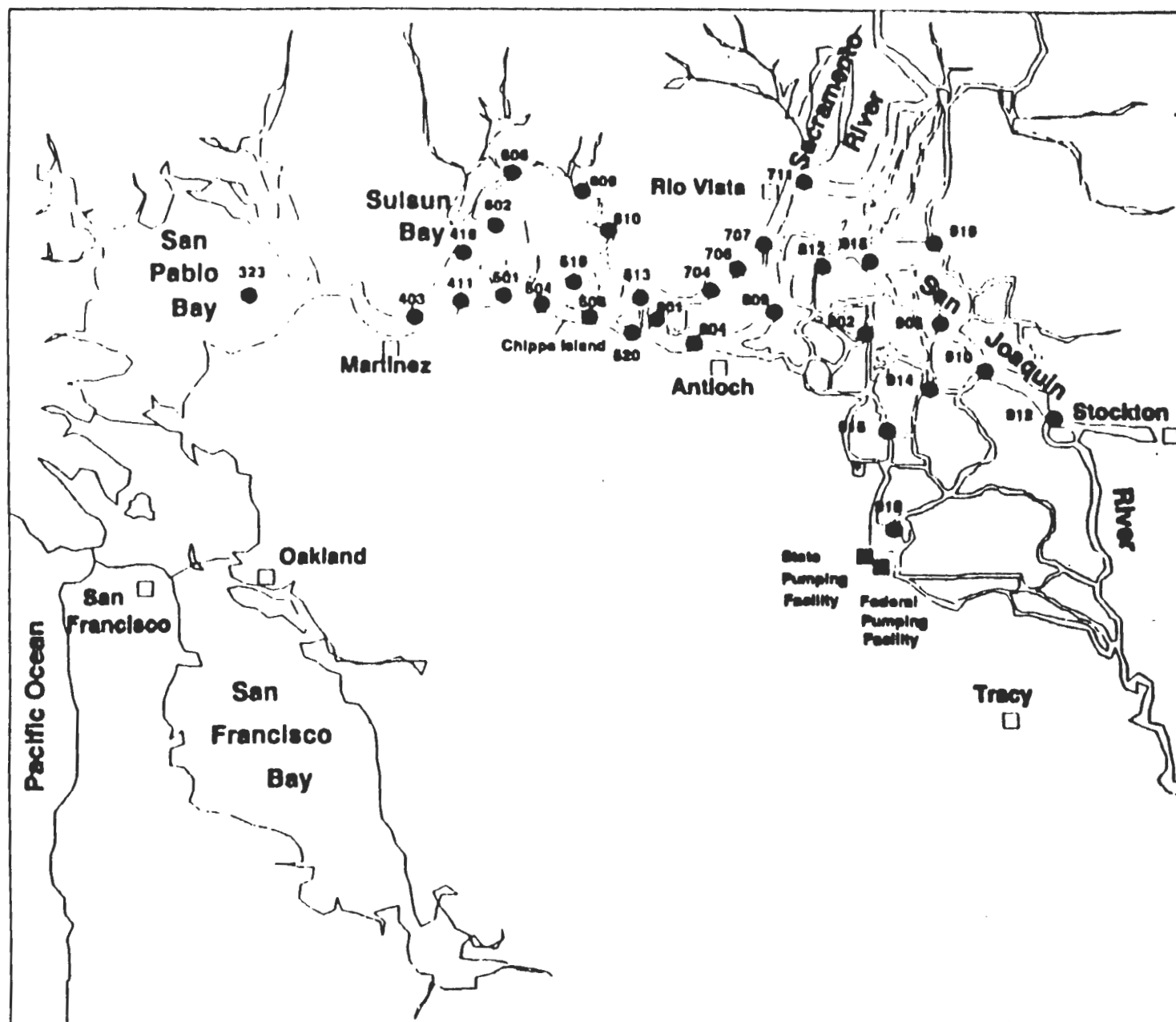
Figure 3. Summer townet survey sampling sites.

this survey and records of these catches were kept in all years except 1967 and 1968. Annual abundance indices for delta smelt were calculated by summing, over all sample sites, the products of: total catch in all tows at a site x water volume in acre feet (Chadwick 1964) represented by that site. Delta smelt abundance indices were calculated only for the first two survey runs since runs 3,4, and 5 were not made in all years. The delta smelt abundance index is the mean of the abundance indices for the two runs after dividing by 1000 to scale the index for convenience. (Appendix C)

This survey provides good coverage of the delta smelt nursery and, in general, should yield an excellent index of young delta smelt abundance during early summer. In high flow years, however, the townet survey may undersample the population because many young smelt are washed downstream to San Pablo Bay or beyond.

The townet survey abundance index shows that annual production of young delta smelt has been quite variable since the survey began in 1959. The peak index of 62.5 in 1978 was 78 times greater than the lowest index of 0.8 in 1985. Abundance has been very low every year since 1983 including, the present year, 1990 (Figure 4). Similar low abundance indices occurred in several
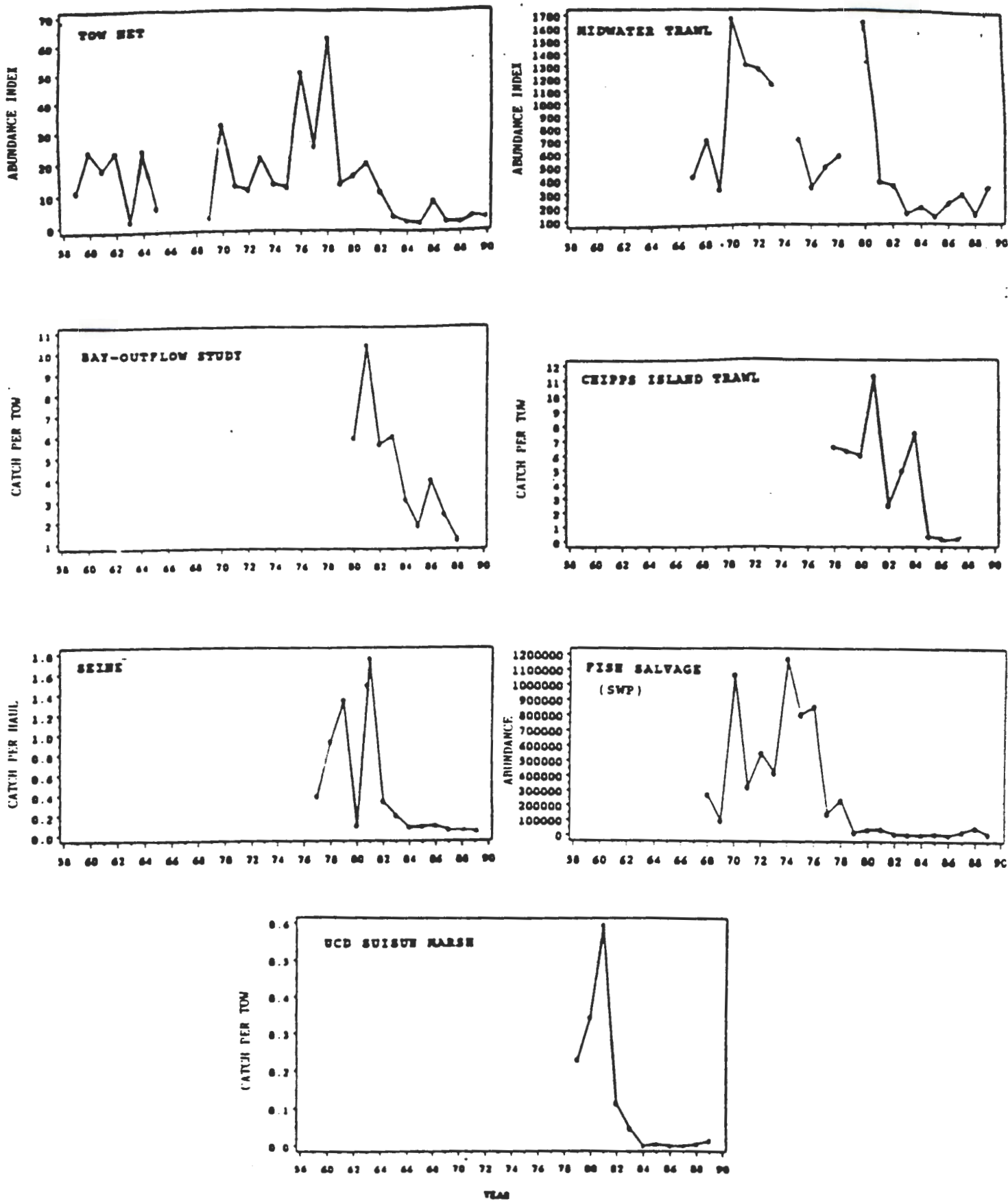
Figure 4. Trends in delta smelt as indexed by seven independent surveys.

20

earlier years (1963,1965,1969), but never for consecutive years. Thus, the townet results indicate that there has been a collapse in the production of young delta smelt.

Fall Midwater Trawl Survey

Starting in 1967, a 12 ft X 12 ft midwater trawl has been used to measure abundance of young-of-the-year striped bass and other species, including delta smelt, during the fall. About 87 sites are sampled from San Pablo Bay upstream to Rio Vista on the Sacramento River and Stockton on the San Joaquin River (Figure 5; Stevens 1977). Originally, the midwater trawl survey was done monthly from August or September through the following March. However, due to extraneous variability in striped bass abundance indices caused by pulses of high winter runoff, sampling has been restricted since 1980 to September through December. Surveys were not conducted in 1974 or 1979 or in November 1969 and September and December 1976.

Delta smelt, which on average are smaller than young striped bass during the fall, probably are at least equally vulnerable to capture by this survey. This survey provides reasonable coverage of the delta smelt population and should yield reasonable measures of the ultimate success of each year class.

Lodi

Stockton

River

Delta Cross Channel

Walnut Grove

Delta-Mendota Canal

Tracy

California Aqueduct

Sacramento River

Federal Pumping Facility

State Pumping Facility

Rio Vista

Antioch

Oakland

San Francisco

Pacific Ocean

Fall midwater trawl survey sampling sites.

22
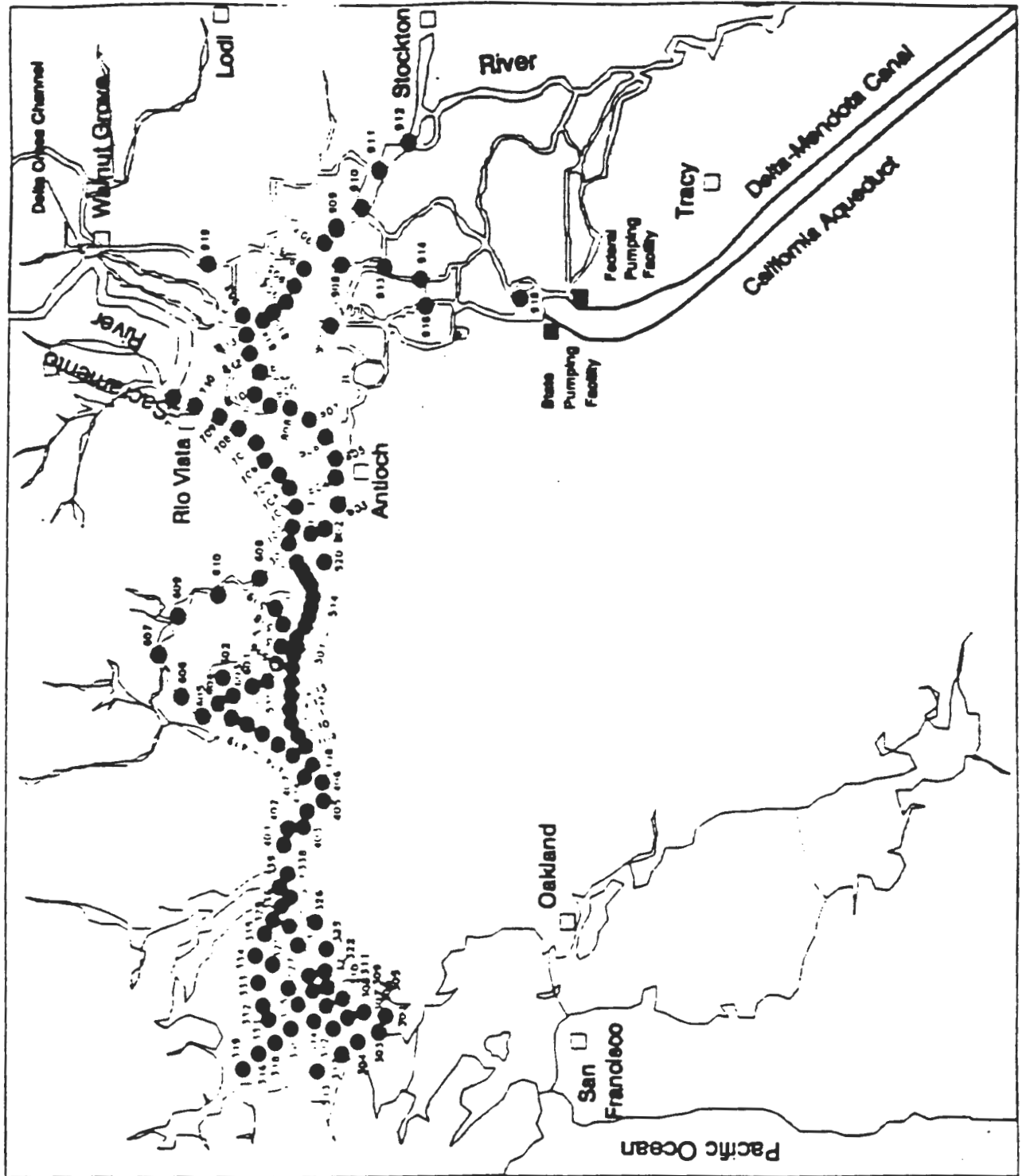
Monthly abundance indices for delta smelt were calculated by summing, over all sampling sites, the product of: the mean catch per 12 minute tow in 17 subareas of the Estuary x the water volume in each subarea (Appendix D). The annual total abundance index is the sum of the monthly indices for September through December. Abundance indices for the surveys missing in 1969 and 1976 were estimated by interpolation or extrapolation of the months actually sampled.

Like the summer townet survey, the fall midwater trawl survey indicates that abundance of delta smelt has been highly variable, and has suffered a major decline (Figure 4). The peak fall index of 1678 occurred in 1970 and was 15 times greater than the minimum fall index of 109 which occurred in 1985. A general downward trend in fall abundance appears to extend back to the peak population of 1970 interrupted by a high index in 1980. The fall index has been consistently low since 1983 and from 1983 to 1988 was lower than in any previous year.

San Francisco Bay - Outflow Study

Midwater trawl catches of delta smelt by the Interagency Ecological Study Program's San Francisco Bay - Outflow Study provide yet another set of delta smelt abundance measures. These measures are based on catches of smelt as small as 25 mm up to

23

adult size and are available from 1980 through 1988. They are based on monthly sampling (12-minute tows) at 42 locations extending from South San Francisco Bay to the western Delta (Figure 6).

The Bay-Outflow Study survey is comprehensive in that it samples monthly throughout the year. Its main deficiency in measuring delta smelt abundance is that it does not sample in the Delta east of Antioch and Collinsville; thus, a portion of the delta smelt's geographical range is not covered. This is particularly important in dry years when the population is concentrated in the Delta.

Typically, the Bay-Outflow survey's delta smelt catches peak from August to October as the new year class grows to a size at which they become vulnerable to capture by the sampling gear (Table 7). Average catches remain moderate through March and then decline into May when the bulk of the adults are spawning upstream from the sampling area and begin to die out. A few remaining adults and the next year class appear in the catches in June and July.

Bay survey catches show a striking decline in delta smelt abundance after 1981 (Figure 4). The 1981 catch rate was about twice that for 1980 but since 1981 there has been an irregular but persistent decline leading to a catch rate in 1988 that was
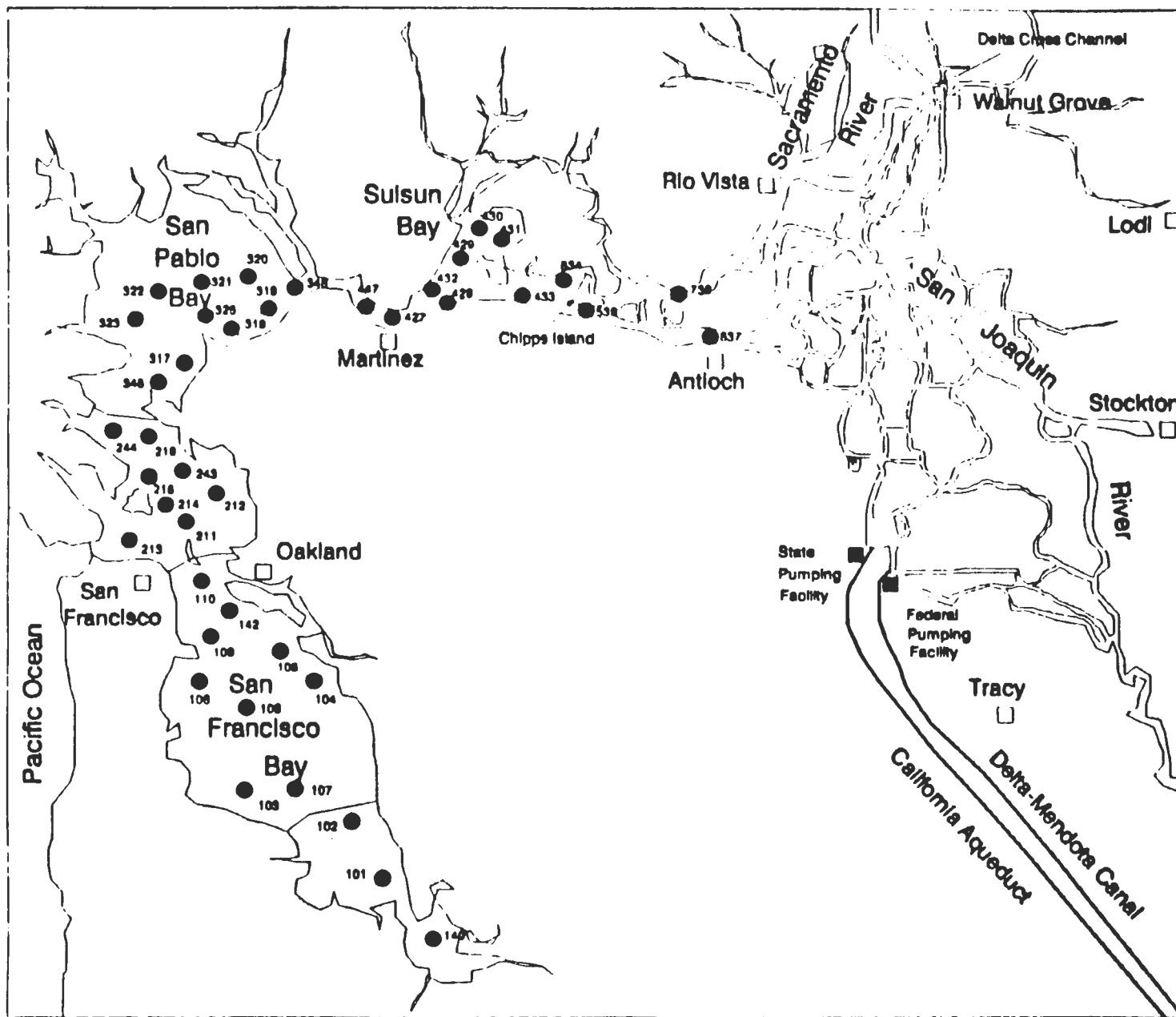
Figure 6. San Francisco Bay - outflow survey sampling sites.

Table 7. San Francisco Bay - Outflow study catches of delta smelt by month and year.

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
1980	1	4	37	2	0	53	31	51	20	36	4		239
1981	27	46	26	19	3	23	15	39	53	19	11	26	307
1982	41	15	9	5	4	4	35	13	7	9	7	22	171
1983	30	12	41	5	1	2	1	15	29	66	14	3	219
1984	2	5	14	21	4	0	5	11	29	5	6	5	107
1985	5	1	1	0	0	1	4	2	1	1	0	21	37
1986	1	3	14	0	0	1	1	23	21	29	9	6	108
1987	6	0	2	1	0	0	6	0	4	0	25	0	44
1988	0	2	1	0	0	0	0	0	16	5	6	0	30
Total	113	88	145	53	12	84	98	154	180	170	82	83	1262

only about one-tenth that for 1981. All of the catch rates since
1984 have been lower than in any previous year. The trend in
catch frequency is consistent with the trend in annual catch
rates. From 1981 through 1984, delta smelt were caught during
all monthly surveys (Table 7). During 1985 and 1986 they were
caught during 9 and 10 surveys, respectively. Delta smelt were
caught only during 6 of the 12 monthly surveys in 1987 and only
during 5 surveys in 1988.

Based on the Bay-Outflow Study data, the current population of
delta smelt is distinctly depressed. Part, but by no means all,
of this depression likely is due to incomplete coverage of the
delta smelt's geographical range: four of the five years since
1983 have been low flow years and the population has been
concentrated in the Delta.

Salmon Survey Trawl and Seine Catches

The Interagency Program has used midwater trawl and seine surveys
to measure annual abundance of young chinook salmon. These
surveys are currently administered by the U.S. Fish and Wildlife
Service. Delta smelt are an incidental catch in these salmon
surveys.

27

The primary trawl survey has been conducted from April through
June, since 1976, at Chipps Island in upper Suisun Bay. Data
from this survey currently are available through 1987. A major
deficiency of delta smelt abundance measures from this trawl
survey is that the survey only samples at one location, thus the
indices are affected by annual differences in delta smelt
distribution. Nevertheless, the catches may still reflect major
changes in population status.

The seine survey generally has sampled about 23 sites at beaches
in the Delta and Sacramento River upstream to the mouth of the
American River (Figure 7). This survey is run several times each
month from January to April, May, or June. Data currently are
available from 1977 to 1989. Since the sampling is entirely in
the Delta and the Sacramento River and in late winter and spring,
catches primarily reflect numbers of delta smelt undertaking
their spawning migration, although, occasionally, young smelt
around 20-30 mm long also have been taken.

As for the other data sources, catches of delta smelt in the
salmon surveys were low during the most recent years. In the
Chipps Island trawl survey, the catch of delta smelt fell
dramatically in 1985 (1984 year class) and remained low in 1986
and 1987 (Figure 4 and Table 8). Catches during these years were
considerably lower than in any previous year except 1977 when a
drought caused salinity encroachment and most of the delta smelt
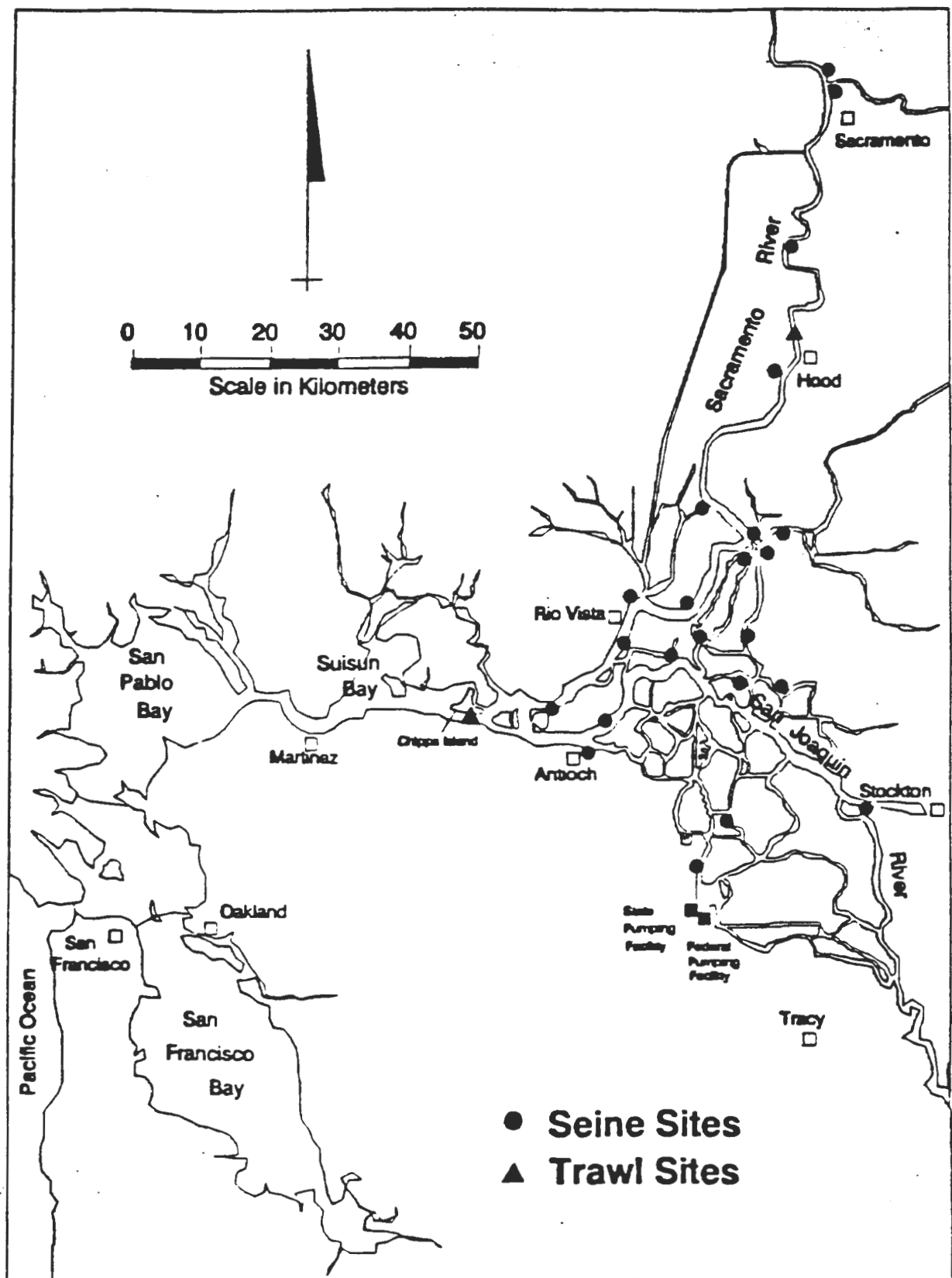
Figure 7. Sampling sites of the salmon trawl and seine surveys.

Table 8. Catch of delta smelt per tow during the chinook salmon trawl survey in the western Delta at Chipp's Island, April-June, 1976-1986. Number of tows in parentheses.

Year	April	May	June	Mean Apr-Jun
1976		3.38(76)	15.54(188)	
1977		0.00(174)	0.01(227)	
1978	2.48(101)	2.28(90)	15.06(174)	6.61
1979	3.83(77)	1.18(78)	14.02(190)	6.34
1980	0.69(65)	0.49(81)	16.88(252)	6.02
1981	14.15(52)	3.69(61)	16.11(124)	11.32
1982	1.46(43)	4.07(121)	2.08(125)	2.54
1983	7.73(67)	4.27(128)	2.85(146)	4.95
1984	15.94(73)	1.85(99)	4.78(164)	7.52
1985	0.91(86)	0.05(298)	0.11(45)	0.36
1986	0.23(95)	0.19(288)	0.28(149)	0.23
1987	0.25(159)	0.21(290)	0.00(43)	0.15

population probably moved upstream from the sampling site. The relatively high average catch of more than seven delta smelt per tow in 1984 (1983 year class) also is inconsistent with the population trend depicted by the broader based surveys and again may reflect an anomalous smelt distribution relative to the single sampling location.

In the seine survey, the lowest average catches of adult delta smelt occurred in 1980 and 1984-1989 (Figure 4 and Table 9). The reason for the low catch in 1980 (1979 year class) is unknown. However, the persistent low catches from 1984-1989 (1983-1988 year classes) are consistent with the population decline exhibited by the fall midwater trawl and summer townet surveys.

Salvage at SWP and CVP Fish Screens

Fish salvage operations at the State Water project (SWP) and the U.S. Bureau of Reclamation's Central Valley Project (CVP) fish screens provide huge samples of fish populations in the Delta; however, a major deficiency relative to measuring fish population trends is that all of the sampling occurs at only one location so the samples are affected by annual variations in the geographical distribution of each species. The salvage is also affected by seasonal and annual variations in water export rates, which affect numbers of fish that are diverted and screening

Table 9. Mean monthly catch of adult delta smelt per haul
during the chinook salmon seine survey in the
Sacramento-San Joaquin Delta, January-April 1977-1987.

Year	Mean monthly catch per haul	No. hauls
1977	0.39	152
1978	0.93	105
1979	1.34	250
1980	0.10	359
1981	1.75	397
1982	0.34	352
1983	0.20	321
1984	0.08	291
1985	0.09	321
1986	0.10	222
1987	0.06	238
1988	0.01	233
1989	0.01	281

efficiency. Also, at times, particularly before 1979 at the CVP, there have been species identification and other data quality problems. Nevertheless, considering the lengthy period of fish salvage information, the records provide another independent, albeit imperfect, source of information on the delta smelt population trend.

Salvage of delta smelt has been monitored since 1968 at the SWP fish screens and since 1979 at the CVP screens. Estimates of total smelt (delta smelt and longfin smelt) salvage provide additional information on smelt trends at the CVP back to 1973. Salvage estimates represent numbers of fish screened from the water that is exported from the Delta, but over-represent numbers of fish that are actually saved because many of these salvaged fish die due to the handling and trucking that is necessary to return fish to the Delta, and to predation by larger fish at the release sites.

Total salvage is estimated from estimates for consecutive periods (typically 2 hours long) based on the salvage rate (fish per minute entering the holding tanks) during each period. These salvage rates are estimated from fish counts ranging from one minute to the total length of the period. Sample counts are expanded to account for the amount of water exported when counts were not made. Because numbers of fish salvaged are affected by

the amount of water diverted, salvage per-acre-foot diverted was also examined.

At the SWP, delta smelt salvage estimates were less than 300,000 fish in the initial two years of sampling, 1968 and 1969, but exceeded 300,000 fish, ranging up to more than 1 million fish in 1970 and 1974 (Figure 8). In 1977, there was a precipitous decline to 146,000 fish from 856,000 fish the previous year. Salvage increased to about 238,000 delta smelt in 1978; however, since 1979, the salvage of delta smelt has been consistently low, less than 60,000 fish, and as low as 3,600 fish in 1986.

At the CVP, the estimated salvage of delta smelt was on the order of 45,000 fish in 1979 and 1980, when smelt species identification began (Figure 9). In 1981, the estimate increased to about 275,000 fish, but since 1982, salvage has been very low, ranging from 2,800 to 34,000 fish.

Despite the lack of smelt species identifications, total smelt salvage estimates suggest that, as at the SWP, CVP salvage of delta smelt tended to be greater from 1973 to 1978 than it has been since 1979. Except in very recent years when the delta smelt population has been very low, the vast majority of identified smelt have been delta smelt at both the CVP and SWP (Table 10). All of the pre-1979 CVP estimates of total smelt
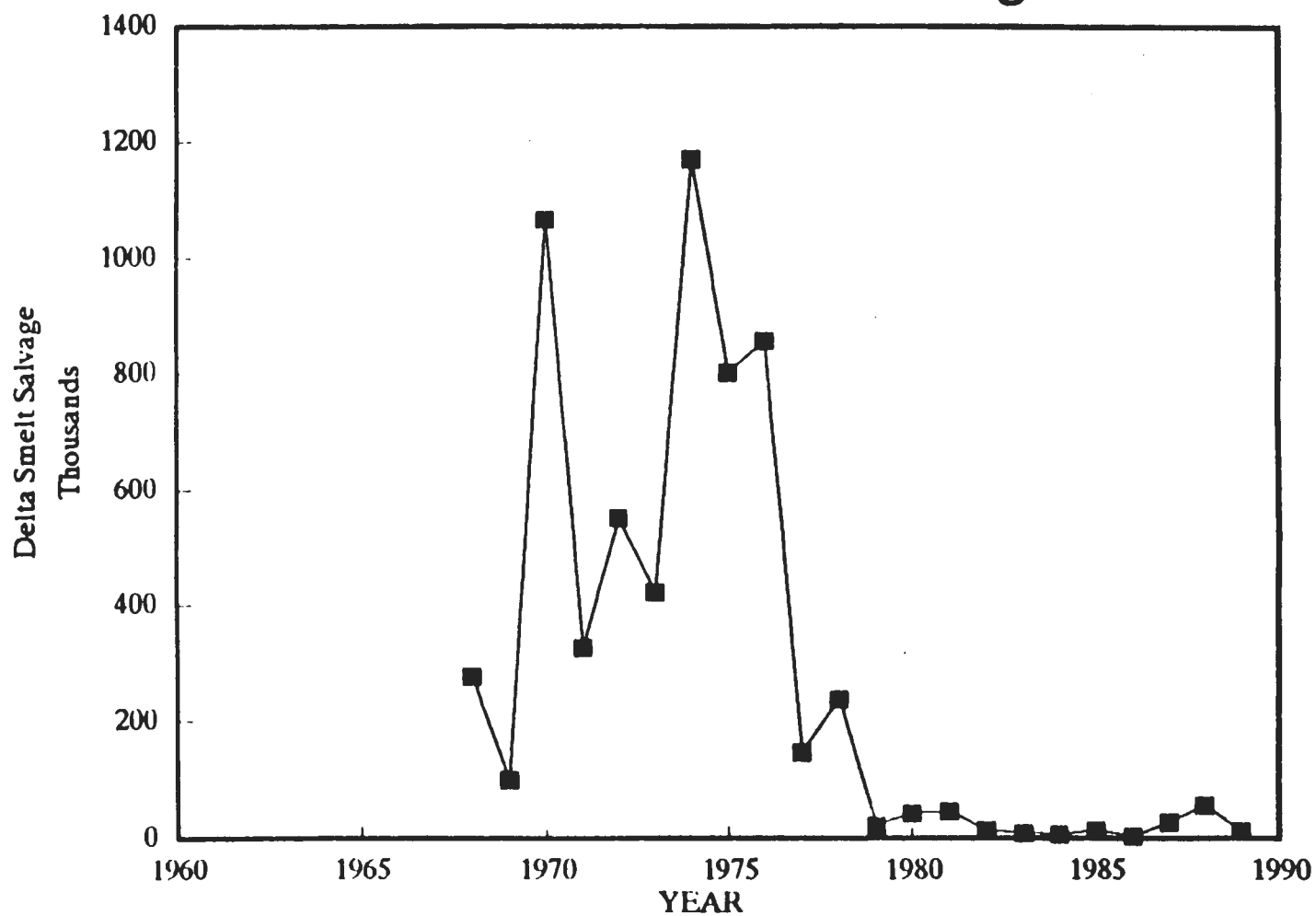
Figure 8. Annual salvage estimates for delta smelt at the State Water Project fish screens.

35

CVP Delta Smelt Salvage
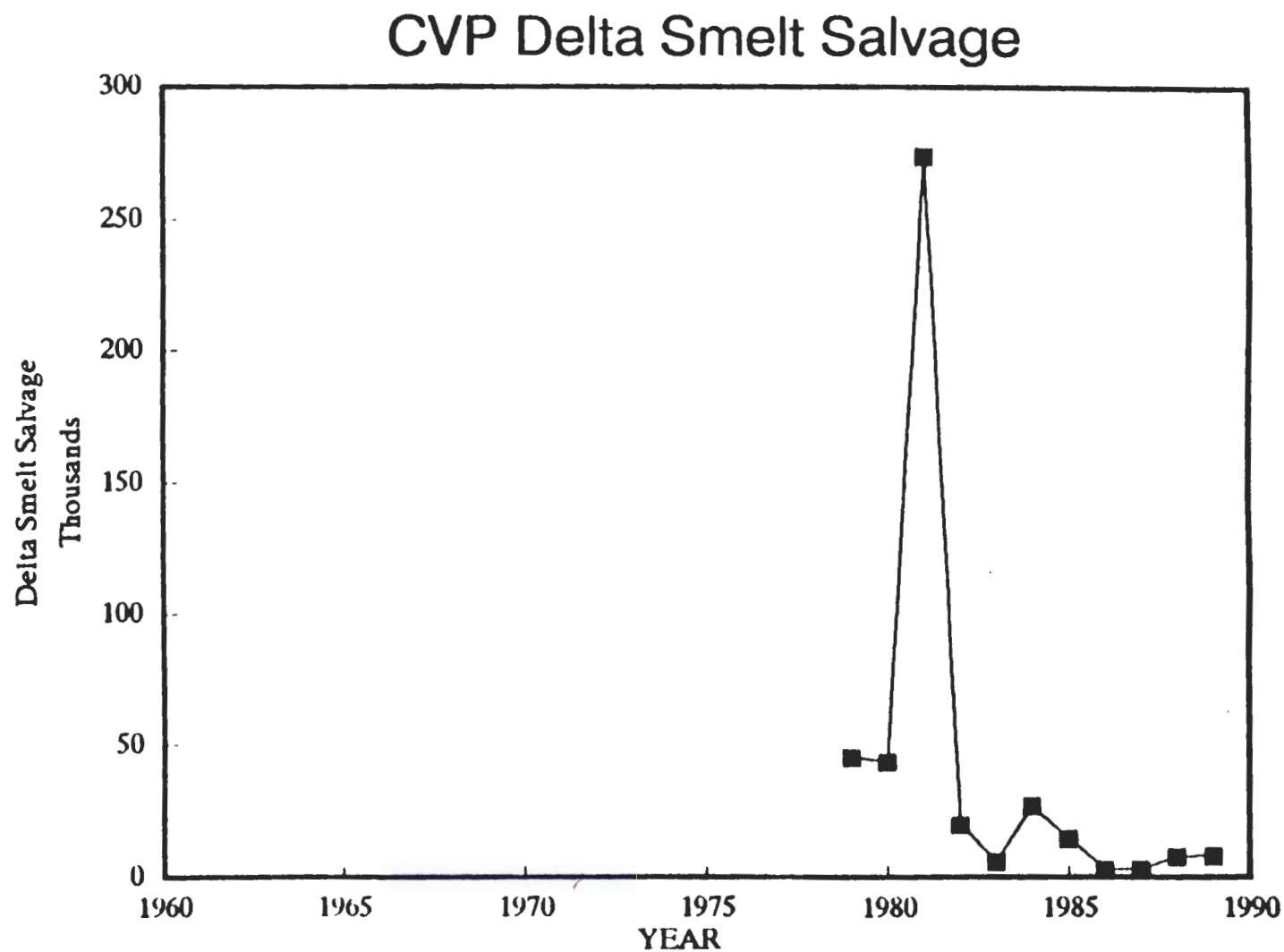
Figure 9. Annual salvage estimates for delta smelt at the Central Valley Project fish screens.

Table 10. Percentage of smelt salvage at State and Federal
Water Project fish screens formed by delta smelt,
1968-1989.

Year	State Water Project Percent delta smelt	Central Valley Project Percent delta smelt
1968	100.0	
1969	99.8	
1970	97.3	
1971	30.0	
1972	98.9	
1973	100.0	
1974	100.0	
1975	100.0	
1976	100.0	
1977	78.6	
1978	98.5	
1979	78.3	54.9
1980	81.6	100.0
1981	94.8	99.9
1982	99.6	100.0
1983	96.5	99.0
1984	88.5	55.4
1985	41.8	80.6
1986	63.0	94.3
1987	34.7	7.4
1988	28.6	54.7
1989	16.4	25.4

salvage varied from about 130,000 to 311,000 fish, a level
equaled subsequently only in 1981 (Figure 10).

Overall, salvage at the SWP and CVP fish screens has trended
substantially downward since 1976 (Figures 4, 8, and 9), despite
a trend of increasing water exports (Figure 11) which would lead
to increased salvage of fish if the smelt population was stable
or increasing. The one anomaly in this trend is the estimated
salvage of 275,000 delta smelt at the CVP screens in 1981.

When sampling effort is considered, by calculating numbers of
smelt salvaged per acre-foot of water diverted, pre-1979
abundance patterns appear to change somewhat, but, as for total
salvage, subsequent salvage per-unit-effort measures are
extremely low (except for 1981 at the CVP) (Figure 12).

Hence, the CVP/SWP salvage records are consistent with the other
data sets indicating that a major decline has occurred in the
delta smelt population; however, considering the sampling
deficiencies (all sampling in one location, seasonal and annual
variability in water export rate, and data quality control
problems) in these data bases, the midwater trawl and townet
surveys undoubtedly provide a better depiction of the timing and
magnitude of decline.

CVP Total Smelt Salvage
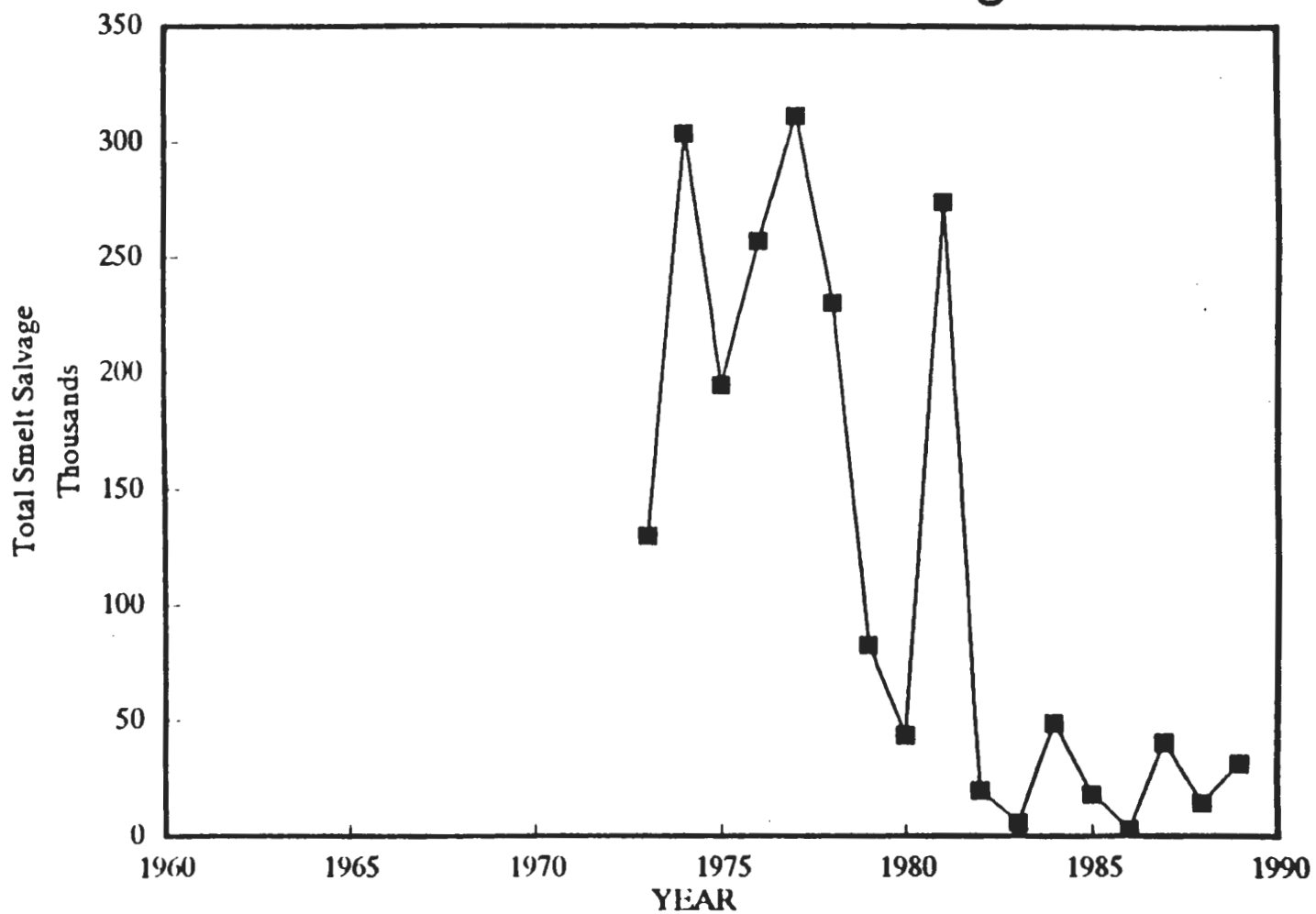
Figure 10. Annual salvage estimates for total smelt (delta smelt and longfin smelt) at the Central Valley Project fish screens.

Delta Exports – Annual Totals
(Acre/Feet)

Figure 11. Trend in annual water exports by the State Water
Project and Central Valley Project.

40

Catch per Unit Effort (SWP and CVP)

No CVP data prior to 1979.

Figure 12. Salvage of delta smelt per acre foot of water diverted by the State Water Project and Central Valley Project.

UC Davis Suisun Marsh Survey

Drs. Peter Moyle and Bruce Herbold and classes at the University
of California, Davis have used otter trawls to sample fish
populations in Suisun Marsh sloughs since 1979. They have
provided us with their delta smelt abundance index for the Marsh
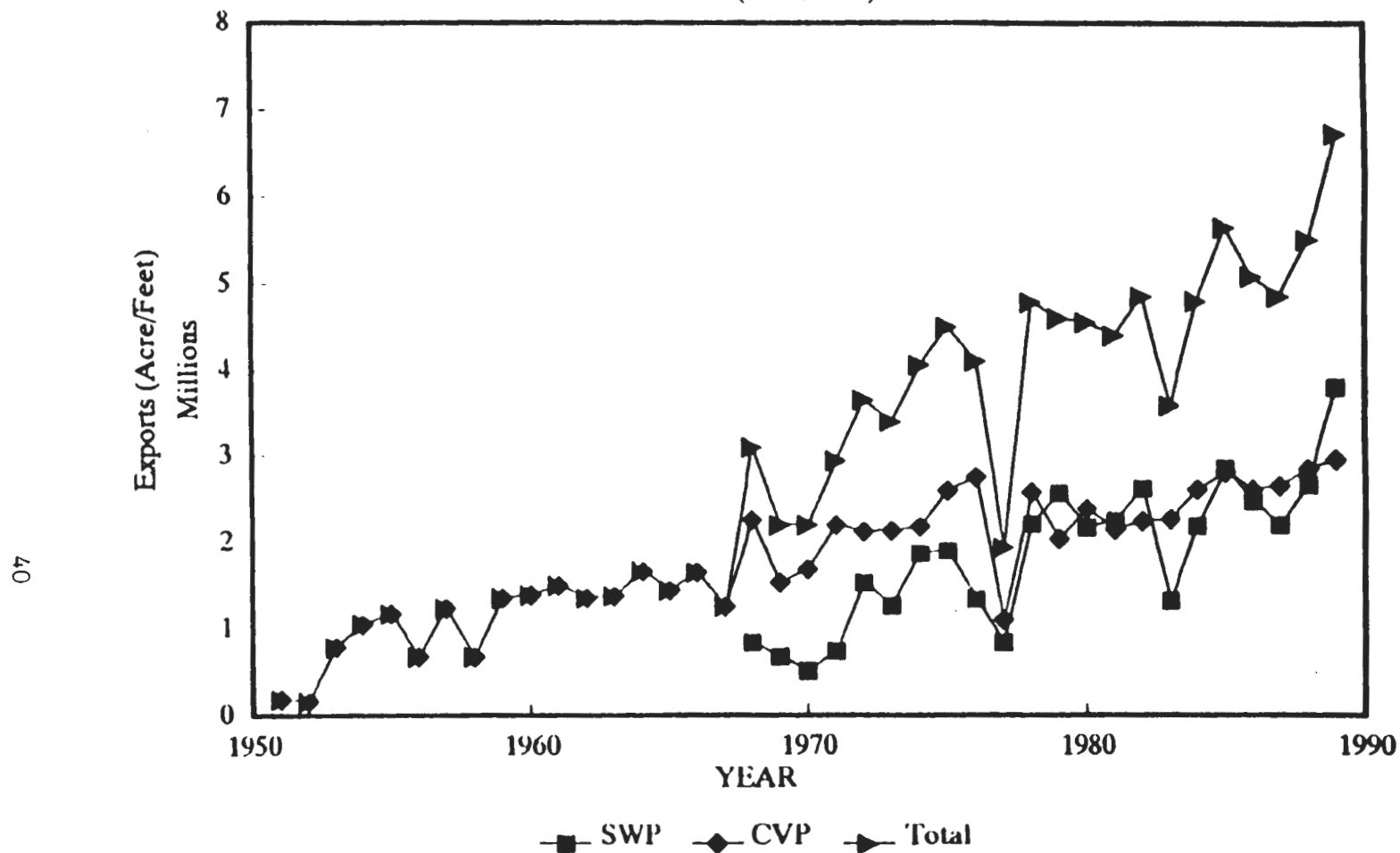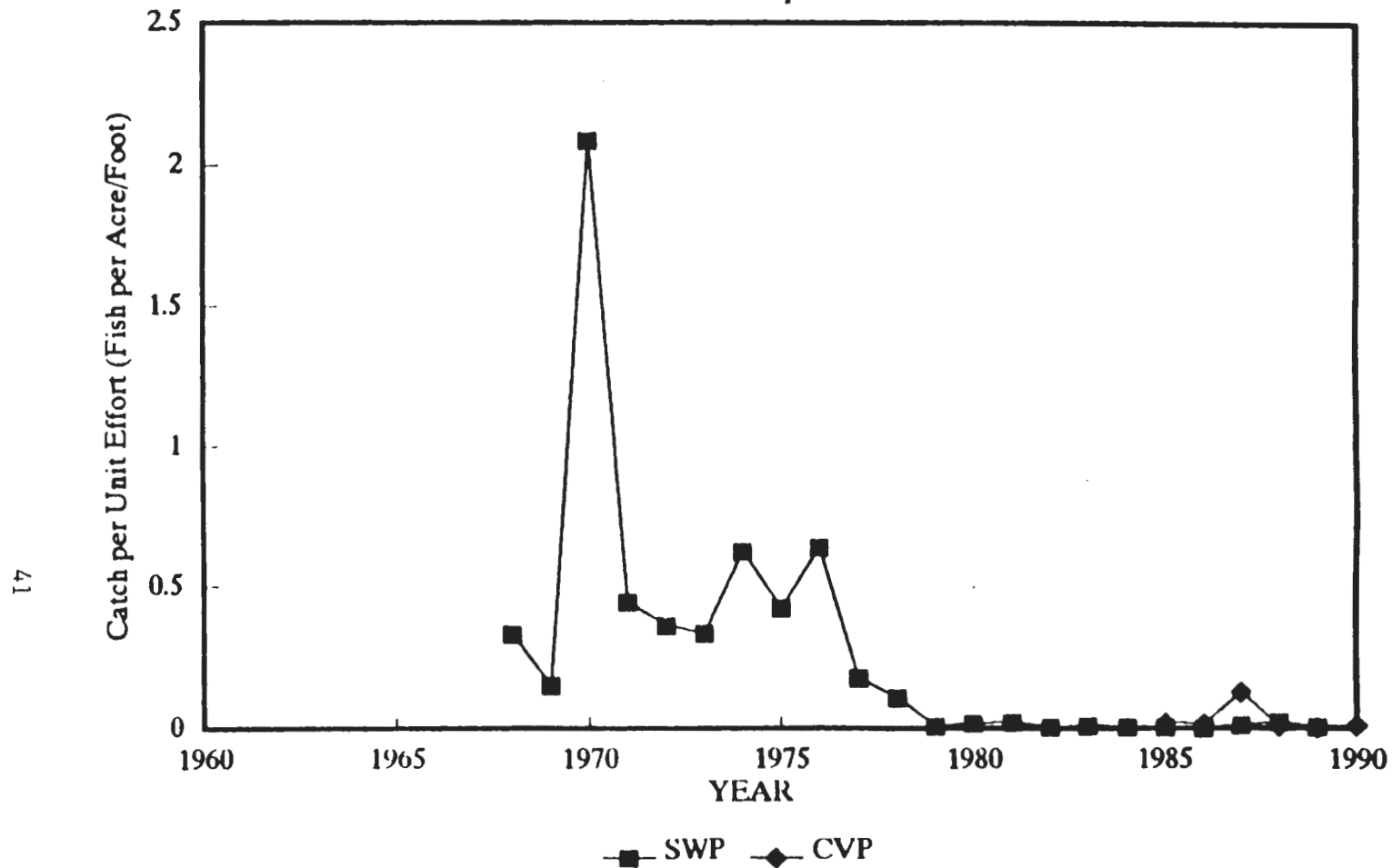based on the number of smelt caught per tow each year. Over the
11-year survey, the UC Davis classes collected 465 delta smelt,
all but one of which was collected before 1984 (Figure 4). Delta
smelt were rather scarce when the survey began in 1979. Catches
improved considerably in 1980 and 1981 with the peak catch of 229
fish occurring in 1981. Subsequently, in 1982 and 1983, delta
smelt abundance declined below the 1979 level, and since 1984
they have been virtually non-existent.

Because the UC Davis sampling locations are limited
geographically and because the geographical distribution of
delta smelt varies annually, we believe that other data sources
provide a better depiction of the overall population trend.
However, the UC Davis survey is consistent with the other data
sources in exhibiting a much lower current population of delta
smelt.

Conclusions Regarding Delta Smelt Abundance Trend

All delta smelt abundance indices have declined in recent years, but the timing of their decline varies somewhat depending on which measure is used. The summer townet survey and fall midwater trawl survey provide the best geographical coverage of the delta smelt population; thus, they provide the best basis for evaluating population trends. Information from the other data sources confirms the general downward trend in delta smelt abundance and allowed additional insight into distribution patterns not covered by the summer and fall surveys.

Based on the summer and fall surveys, the delta smelt population has been consistently low every year since 1983. While the population had been as low or nearly as low in some previous years, no multiple year period of low abundance had occurred previously during the period of record beginning in 1959.

Looking at the decline by geographical areas (Figures 13 and 14), it is apparent that the delta smelt decline may have begun earlier in the south and east delta than in the rest of the Estuary. An earlier decline in these areas is consistent with the decline suggested by the fish salvage data from the water project diversions in the south Delta.

43
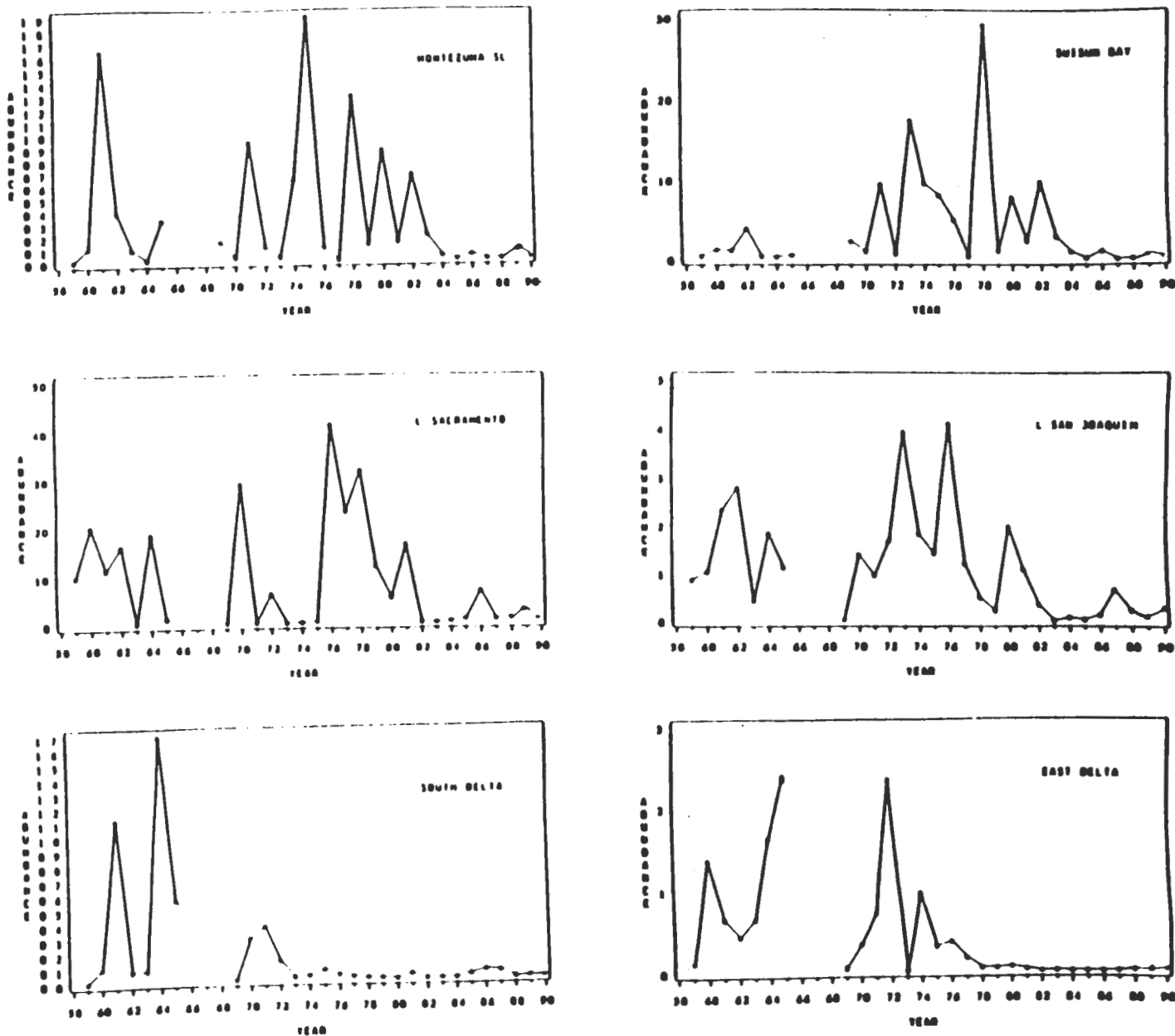
Figure 13. Abundance of delta smelt by area based on the summer townet survey. L. Sacramento is the Sacramento River between Collinsville and Rio Vista. L. San Joaquin is the San Joaquin River between Antioch and San Andreas shoal west of the Mokelumne River.
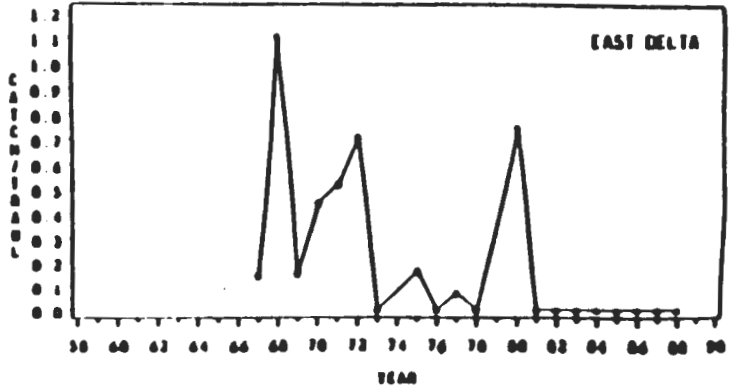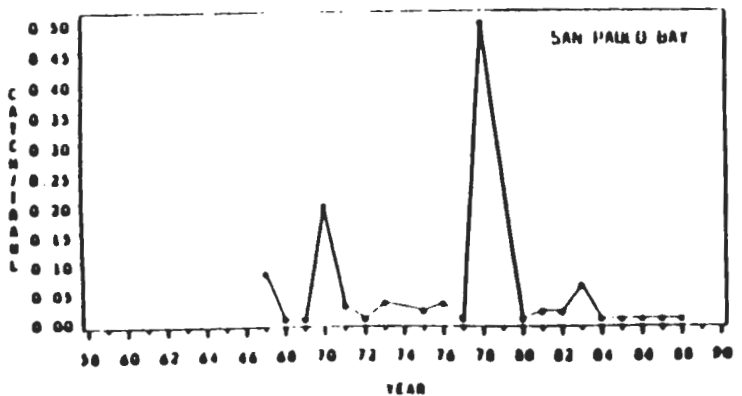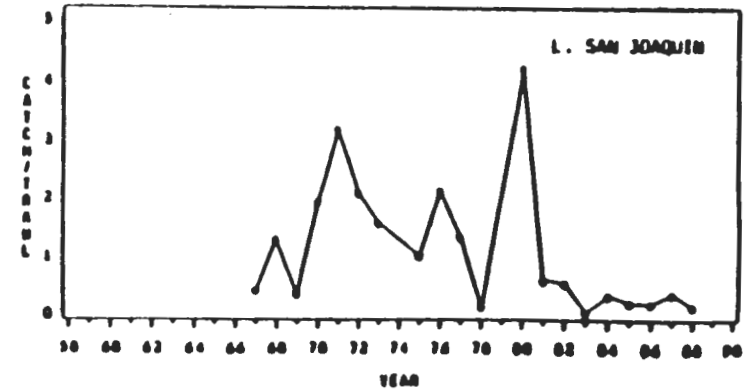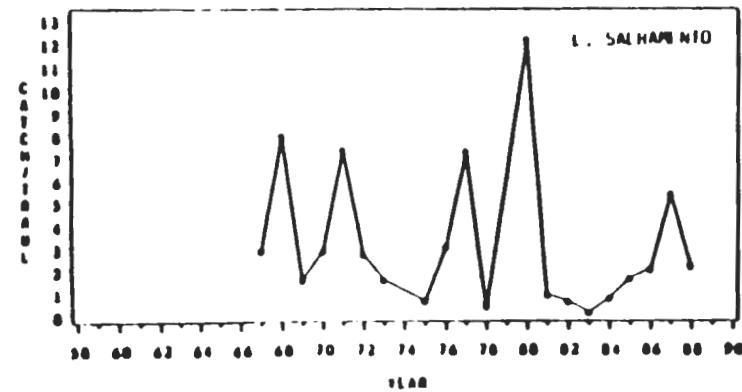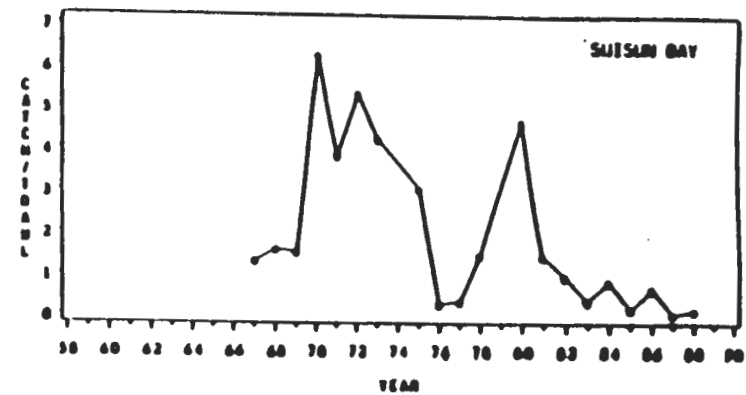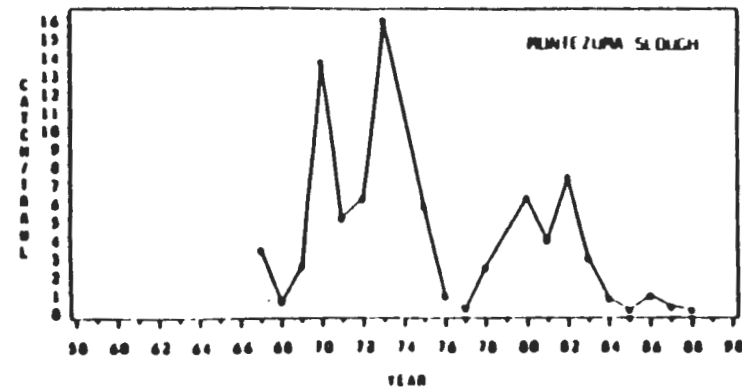
Figure 14. The catch-per-tow of delta smelt in the midwater trawl
survey by areas comparable to those used for the
townet survey (Figure) except for the addition of
San Pablo Bay and the deletion of the South Delta
which was not sampled after 1975.

45

Except for the years since 1981, the fall indices do not show good agreement with the summer indices, possibly reflecting imprecision in one or both data sets, or that before 1981 environmental factors modified year class strength substantially between summer and fall. In either case, the delta smelt population decline since 1983 appears to have been a direct result of lower recruitment to the summer population.

For further insight into the nature of the decline, we examined the percent of the townet and midwater trawl survey tows that caught one or more delta smelt and the mean catch in those tows (Figure 15). In the townet survey the frequency of tows capturing smelt has declined as has the mean catch in those tows.

These trends indicate that the summer population has fewer and less dense aggregations than it did previously. The frequency of fall tows capturing delta smelt has also declined, but the mean catch in those tows has not changed appreciably. Hence, in the fall there now are fewer aggregations, but those present are similar in density and/or size to those of the past. This difference in summer and fall data may reflect an increased tendency toward schooling behavior as the smelt grow older. Since delta smelt abundance has declined in all areas (Figures 13 and 14), it is apparent that the decline in the number of tows
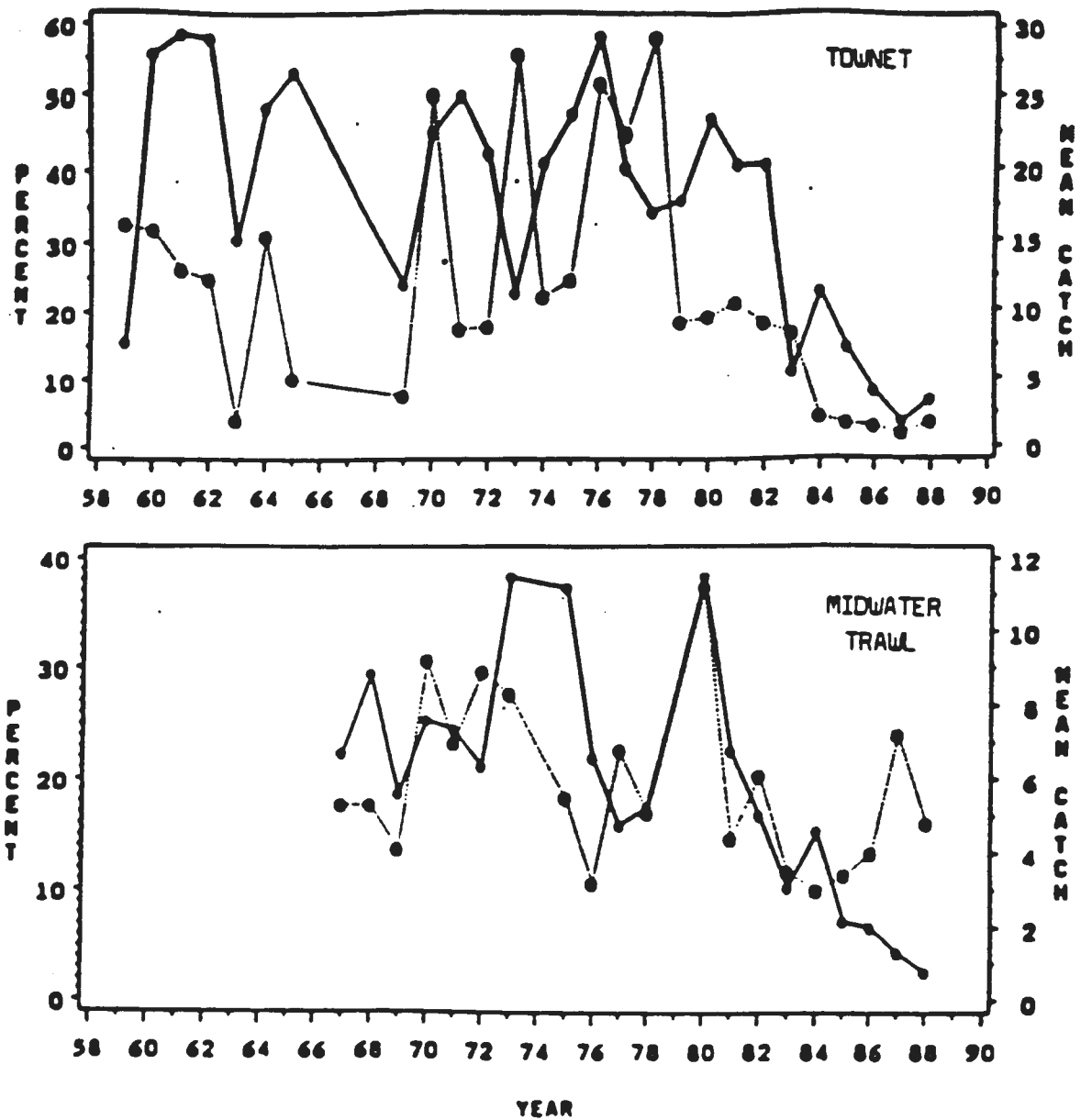
Figure 15. The percent of tows capturing delta smelt (solid line)
            and the mean catch of delta smelt in those tows
            (dotted line).

capturing them is not due to a diminishing of the delta smelt's range within the Estuary. Instead, the decline is simply due to reduced probability of capture associated with a general decline in abundance.

To determine if the apparent decline in delta smelt abundance was statistically significant, we used an Analysis of Variance (ANOVA) with Tukey's test for grouping years for which there are no significant differences. This analysis was based on logarithmic transformations of catch per tow in the townet and trawl surveys. The ANOVA demonstrated significant differences between years and the Tukey's ranking generally separated the recent years into a common group separate from earlier years although there were a few exceptions such as 1959, 1963 and 1969 in the townet survey groupings (Tables 11 and 12).

Population Size

To address the question of delta smelt abundance, we multiplied, for the fall midwater trawl survey, the ratio of delta smelt juveniles to young striped bass by rough estimates of striped bass population size which are available for 8 years. Using this approach, albeit imperfect due to unknown catch vulnerabilities, we estimate that the fall delta smelt population is now several hundred thousand fish (Table 13). In the early 1970s, estimates were on the order of 2 million fish.

Table 11. Tukey's studentized range test for detecting differences in $\log_{10}$ mean catch per tow of delta smelt by the townet survey. Means with the same Tukey grouping letter are not significantly different (p. <0.10).

Tukey Grouping									Mean	N	Year
A									0.56	174	1961
A	B								0.53	167	1976
A	B	C							0.48	186	1962
A	B	C	D						0.43	176	1971
A	B	C	D						0.43	186	1964
A	B	C	D						0.42	135	1960
A	B	C	D						0.41	175	1975
A	B	C	D						0.40	184	1978
	B	C	D	E					0.38	183	1980
	B	C	D	E					0.38	172	1974
	B	C	D	E					0.38	186	1970
	B	C	D	E					0.36	176	1982
		C	D	E					0.35	152	1977
		C	D	E					0.35	176	1981
		C	D	E	F				0.38	186	1965
			D	E	F	G			0.29	172	1972
			D	E	F	G	H		0.27	178	1973
				E	F	G	H	I	0.22	189	1979
					F	G	H	I	0.17	134	1959
					F	G	H	I	0.16	181	1986
						G	H	I	0.14	186	1963
							H	I	0.12	151	1983
							H	I	0.11	182	1969
							H	I	0.10	161	1984
								I	0.07	159	1988
								I	0.07	175	1987
								I	0.05	164	1985

49

Table 12.   Tukey's studentized range test for detecting differences
             in log_{10} mean catch per tow of delta smelt for the midwater
             trawl survey. Means with the same Tukey grouping letter
             are not significantly different (p <0.10).

Tukey Grouping						Mean	N	Year
A						0.31	326	1980
A						0.30	324	1973
A	B					0.25	295	1975
	B	C				0.20	385	1970
	B	C				0.19	404	1968
		C	D			0.17	390	1971
		C	D	E		0.17	364	1972
		C	D	E	F	0.14	335	1967
		C	D	E	F	0.14	332	1981
			D	E	F	G	0.11	332	1969
			D	E	F	G	0.11	478	1977
				E	F	G	0.10	456	1978
				E	F	G	0.10	358	1982
					F	G	0.08	364	1986
					F	G	0.08	353	1984
					F	G	0.07	386	1987
						G	0.05	370	1983
						G	0.04	358	1985
						G	0.04	369	1988

50

Table 13. Estimates of Delta Smelt abundance based on the ratio of Delta smelt abundance to young striped bass abundance in the fall midwater trawl survey multiplied by population estimates of young striped bass derived from a life table analysis.

Year	Striped Bass Index	Delta Smelt Index	Ratio Smelt: Bass	Striped Bass Population (in millions)	Delta Smelt Population (in thousands)
1968	4109	696	.17	1.8	300
1970	8144	1677	.21	8.1	1670
1971	9069	1306	.14	11.9	2670
1972	6101	1267	.21	12.7	2630
1975	4538	698	.15	1.6	240
1977	844	483	.57	0.4	230
1984	6584	181	.03	11.8	350
1985	1757	109	.06	4.7	280

Population Age Structure

We examined length-frequency data for the townet and midwater trawl surveys for 1977, 1978 and 1980 to learn more about the size and age structure of the population (Figures 16 and 17). In both data sets, two year classes of delta smelt were evident. The juveniles from the current year's production form one group in the size range of 15 mm to about 65 mm in summer and up to about 90 mm in the fall. Second groupings of larger smelt up to 130 mm indicate that a few adults survive the rigors of spawning and live into the following winter. However, since these larger adults are so scarce, one-year old fish form almost the entire spawning population each year.

FACTORS AFFECTING DELTA SMELT ABUNDANCE

What factors regulate abundance of each year class of delta smelt? Considering that most delta smelt spawn only once, the abundance of the previous year class and its egg production is potentially important. We evaluated the potential role of egg production by examining spawner-recruit relationships using the summer townet survey data alone, a combination of the summer townet data and the midwater trawl data, and the midwater trawl data alone (Figure 18). In the best case, that for the midwater trawl data alone, the spawning stock abundance accounted for
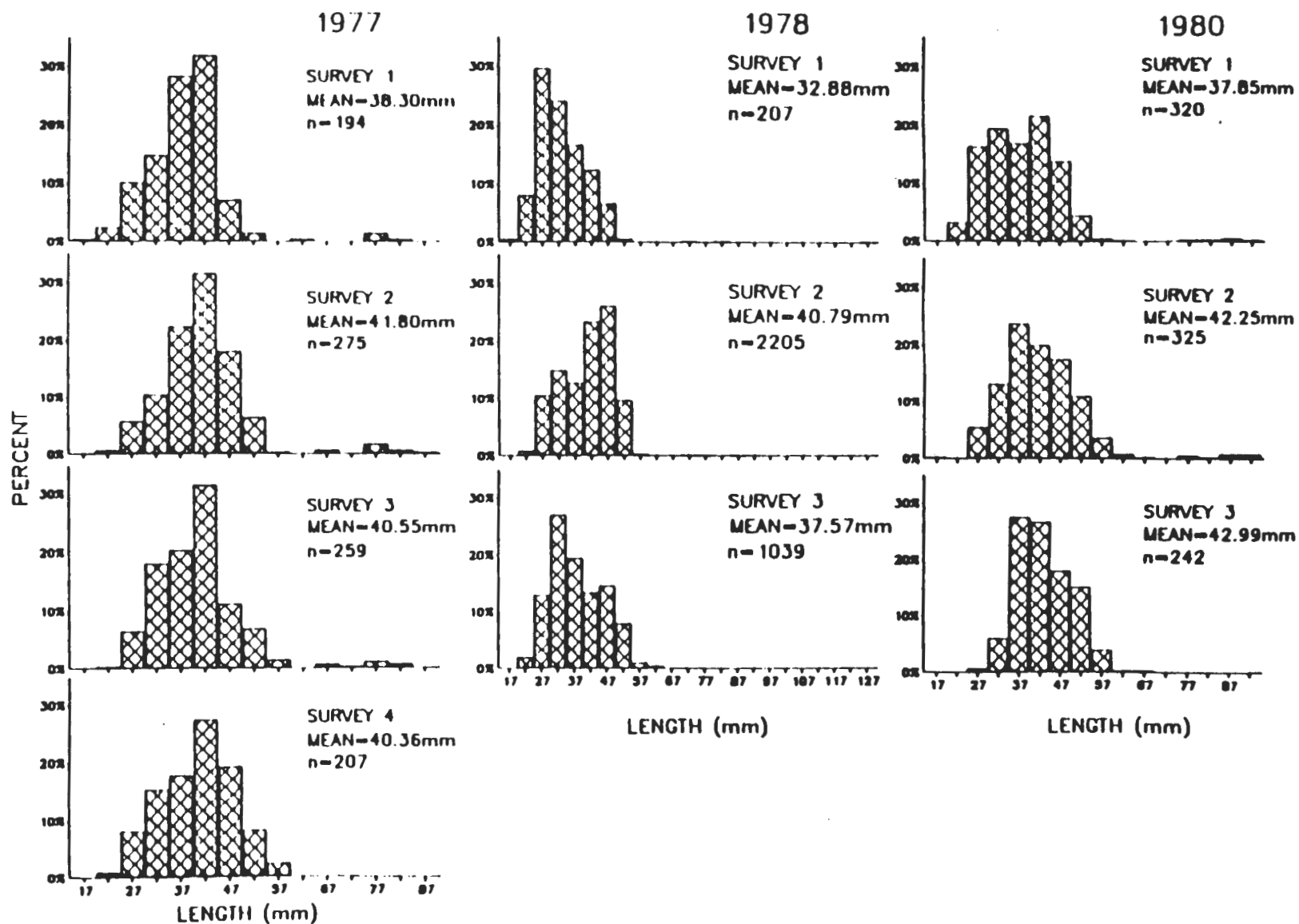
Figure 16. Length frequency distribution of delta smelt catches in the 1977, 1978 and 1980 townet surveys.
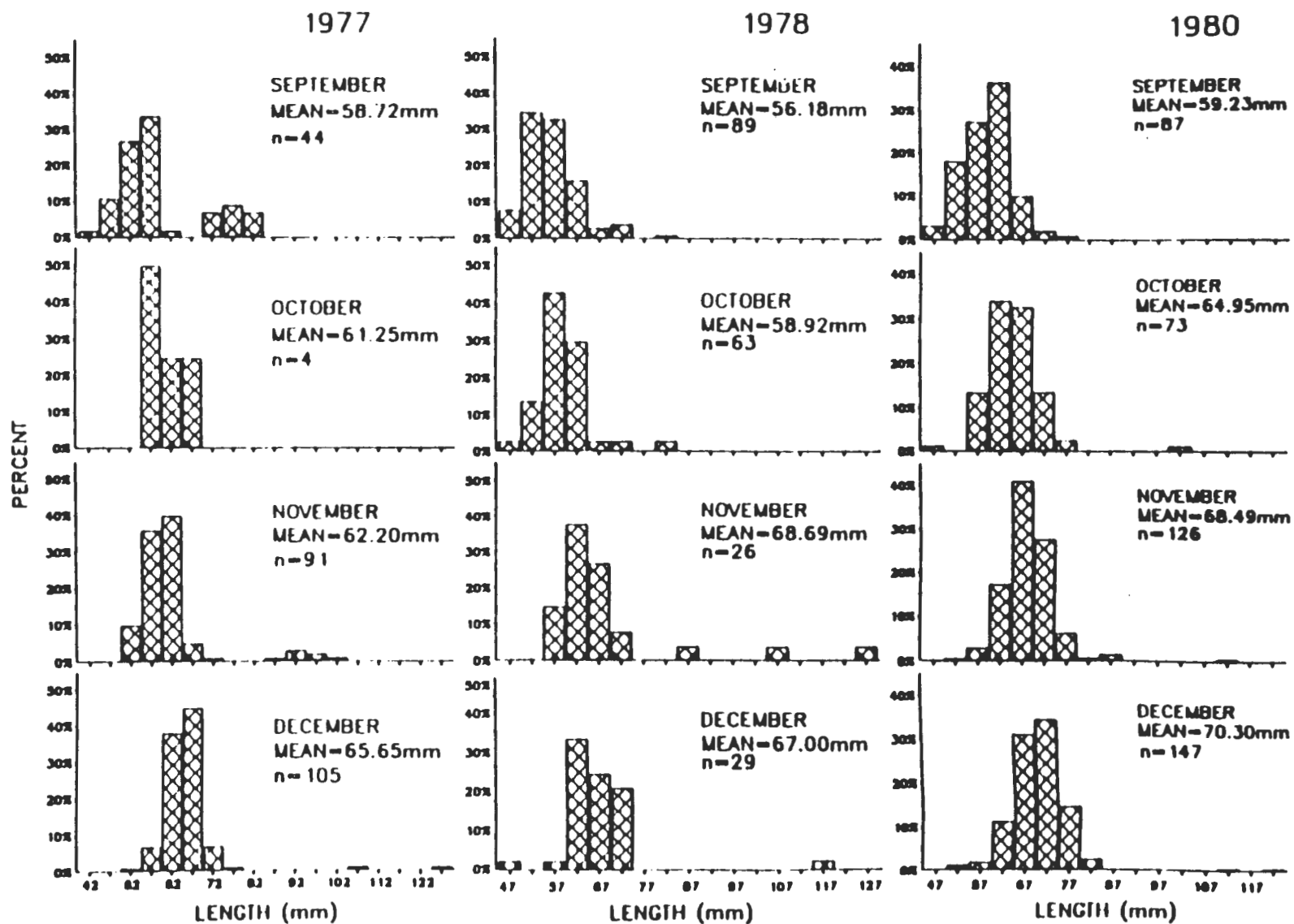
Figure 17. Length frequency distribution of delta smelt catches in the 1977, 1978 and 1980 midwater trawl surveys.

Figure 18. Spawner-recruit relationships for delta smelt: (a) the townet index (spawners) and the townet index for the following years (Recruits), (b) the midwater trawl index (spawners) and the townet index the following year (Recruits) and (c) the midwater trawl index (spawners) and the midwater trawl index the following year (recruits).

55

about one-quarter of the variability in recruitment (abundance ofthe next year class).

If egg production was the sole factor influencing year class success, the delta smelt population would be stable. In reality, abundance indices (based on fall trawl survey) have varied from 105 (1985) to 1840 (1980), a 17.5 fold difference. Also, as described previously, until 1981, the fall and summer indices did not show good agreement. These facts and the relatively weak spawner-recruit relationships strongly suggest that abundance of a delta smelt year class largely depends on the environmental conditions experienced by the eggs and young fish. We used multiple regression analyses to search for environmental factors which may affect delta smelt abundance. Specifically, we examined potential effects of:

1)   Delta outflows - Moyle and Herbold (1989) suggest that delta
     smelt year class production is favored by moderately high
     flows which place the primary nursery area in the Suisun Bay
     region. Outflows are known to influence abundance of
     several other species in the Estuary including striped bass
     (Turner and Chadwick 1972, CDFG 1987), longfin smelt
     (Spirinchus thaleichthys), American shad (Alosa sapidissima)
     (Stevens and Miller 1983) and bay shrimp (Crangon sp) (Bay-
     Delta Project, unpublished). We included outflow and
     outflow^2 terms. The outflow^2 term allows the regression

predictions to decline if smelt abundance peaks at moderate
flows and declines at higher flows.

2) <u>Diversions from the spawning and nursery area</u> - Major State
and Federal water projects, Pacific Gas and Electric Company
power plants, and other industry and local agriculture
operations divert huge amounts of water from the Delta
during the spawning and nursery period (pages 62 to 73).
Many young and adult delta smelt entrained by these
diversions are removed from the population. Recent analyses
(Stevens et al. MS) indicate that such entrainment losses
have caused a severe decline in the Sacramento-San Joaquin
Estuary's striped bass population. We used total water
exports as measures of diversions.

3) <u>Food supply</u> - Delta smelt feed on zooplankton, especially
copepods (pages 4 to 6). Thus, availability of these
zooplankton for young smelt potentially could affect their
growth, survival and abundance. We used copepod densities
(exclusive of nauplii and <u>Sinocalanus</u> <u>doerii</u>) to measure
food supply.

4) <u>Reverse flow</u> - Due to water project pumping in the south
delta the lower San Joaquin River frequently flows backwards
and transports small fish toward the diversions (pages 64 to
67). Moyle and Herbold (1989) suggest that this process is
detrimental to delta smelt. We used the number of days of
net reverse flow at Jersey Point on the San Joaquin River as
our measure of reverse flow.

5) <u>Water temperature</u> - Temperatures may affect delta smelt abundance through effects on growth and mortality. We used average maximum temperatures from the U.S. Geological Survey monitoring station on the Sacramento River at Freeport to provide a general, albeit imperfect, indication of annual temperature conditions.

6) <u>Water transparency</u> - Water transparency may reflect general productivity of the Estuary and/or vulnerability of delta smelt to predation by other fishes. Delta waters have tended to become clearer in recent years (California Fish and Game 1988). We used average Delta-Suisun Bay secchi disc readings from the Bay-Delta project's zooplankton survey as a general indicator of water transparency.

We tested one, two and three variable models for the summer townet survey and fall midwater trawl survey indices using all combinations of these environmental factors (RSQUARE procedure in SAS version 5, 1985). Both abundance indices were evaluated against averages of the environmental factors during the March-June spawning and early nursery period, and the fall midwater trawl index was also evaluated against averages for the July-October late nursery period.

Care must be taken in interpreting results of such regression searches, as even the moderate number of input variables that we used, may lead to some chance relationships which are spurious.

58

At best, any of the regression models should only be considered as "suggestive" mechanisms which require further testing.

R^2 values indicate that none of the models based on March-June environment explain a satisfactory amount of variability in smelt abundance (Appendices E and F). Of the July-October variables, copepod abundance and water transparency dominated the best models and themselves accounted for almost 70% of the variability in the midwater trawl index (Appendix G). However, despite this apparent association between delta smelt abundance and July-October copepods and water transparency, the importance of these factors should, at best, be considered tentative. Comparisons between the summer townet survey and fall midwater trawl indices suggest that since 1983, at least, delta smelt year class strength has been set before July.

THREATS

Numerous factors potentially threaten the existence of the delta smelt which has probably been at all-time low abundance levels since 1983. Discussion of several of the most obvious factors follows.

Food Supply

Zooplankton abundance in the Estuary has been monitored by the
Department's zooplankton monitoring survey since 1972.
Zooplankton also have been monitored in the spring since 1984 by
the striped bass egg and larva survey. These surveys demonstrate
that densities of _E. affinis_, the most common copepod in the
delta smelt's diet, were relatively stable prior to 1988.
However in 1988, a major decline in _E. affinis_ occurred over much
of the delta smelt's range (Table 14). This decline coincided
with the accidental introduction and population explosion of the
clam, _Potamocorbula amurensis_, (pages 78 and 79). The most
recent years, 1988 and 1989, provide somewhat ambivalent results
regarding the impact of the decline of _E. affinis_ on delta smelt.
In 1988, the midwater trawl index for delta smelt was at its next
to lowest level; however, in 1989, while still very low from a
historic perspective, this index rebounded to its highest level
since 1983. Nevertheless, the recent decline in this major diet
component, still must be considered as a potential threat to the
delta smelt's recovery unless other food resources compensate or
E. affinis recovers to its former abundance.

Table 14. Mean Density of _Eurytemora_ _affinis_ per m³ in the Estuary during May and June.

Year	EC < 1000 uS Zooplankton Survey	Egg and Larva Survey	EC > 1000 uS Zooplankton Survey	Egg and Larva Survey
1972	588		4301	
1973	589		1884	
1974	1017		4980	
1975	378		1378	
1976	369		1794	
1977	370		2232	
1978	639		4172	
1979	262		2390	
1980	176		1466	
1981	258		1410	
1982	533		3246	
1983	806		2673	
1984	128	64	1556	737
1985	51	50	1006	465
1986	485	82	2504	1128
1987	389	--	1437	--
1988	106	48	88	58
1989	---	22	--	29

Low Spawning Stock

Our evaluation of factors regulating delta smelt abundance failed to show that spawning stock abundance had a major influence on delta smelt year class success (pages 52 to 56). Nevertheless, the relatively low fecundity of this species and their planktonic larvae, which undoubtedly incur high rates of mortality, means that annual reproduction must be accomplished by fairly large numbers of fish if the population is to perpetuate itself (Moyle and Herbold 1989). Thus, while the stock abundance may not have been an important factor in the past, present or future low stock levels may inhibit potential for population recovery. Pimm et al. (1988) show that small species with variable populations, like delta smelt, become increasingly vulnerable to extinction as their populations decrease.

Entrainment in Water Diversions

Delta smelt larvae are lost to entrainment in water diversions of the CVP, SWP, and Delta agriculture, the Pacific Gas and Electric Company (PGE) and other industry using water from the Estuary.

The PGE power plant intakes are screened, but these screens are ineffective on larval fish. In 1978-1979, more than 50 million and 16 million smelt larvae (delta smelt & longfin smelt - -

62

larval smelt are difficult to identify to species and there has
not been an attempt to identify them during any of the
entrainment monitoring programs) were estimated to have been
entrained at PGE's Pittsburg and Contra Costa power plants,
respectively (PGE 1981a, 1981b). Also, estimates of impingement
of larger delta smelt juveniles on the power plant intake screens
were 11,000 fish at Pittsburg and 6,400 fish at Contra Costa.

There is no information available on delta smelt losses in the
myriad of delta agriculture diversions which are not screened at
all. However, during sampling on 20 days from November 1980-May
1981 and September 1981-March 1982, the delta smelt was the most
numerous species entrained in the unscreened Roaring River Slough
diversion from Montezuma Slough for water distribution in the
Suisun Marsh (Pickard et al. 1982). This sampling, which
generally consisted of placing a net over 1 of 8 intake culverts
for several hours, captured 5,841 delta smelt.

Substantial entrainment losses also occur at the CVP and SWP
despite their intakes being miles from the primary spawning and
nursery areas. These losses occur due to the magnitude of the
water project diversions, their impact on Delta flow patterns,
and the tendency for young delta smelt to be transported and
dispersed by river and estuarine currents.

63

The CVP and SWP pumps are located at the southern edge of the Delta, but pumping rates usually exceed the flow of the San Joaquin River entering the Delta from the south; therefore, most of the water that they export must come from the Sacramento River. Approximately the first 3,500 cfs of flow exported from the Sacramento River crosses the Delta through the CVP's Delta Cross Channel and Georgiana Slough near Walnut Grove and flows to the pumps through natural channels upstream from the mouth of the San Joaquin River. Young smelt that were spawned in the water transport channels or in the Sacramento River upstream from Walnut Grove would be particularly vulnerable to this water management scheme. At higher export rates, water is drawn up the San Joaquin River from its junction with the Sacramento River (Figure 19). Such net upstream flows in the San Joaquin River are typical in all but wet springs, and in the summer and fall of all years. The upstream flows entrain young smelt from the western Delta and carry them to the water project intakes.

Moyle and Herbold (1989) found that high frequencies of reverse flows in the San Joaquin River during spring were always associated with low abundances of delta smelt in Suisun Bay in the fall (Figure 20) while low frequencies of reverse flows sometimes were associated with high abundances of delta smelt. They (MS) also point to a trend of increasing reverse flows in the San Joaquin River, especially during the spawning months.
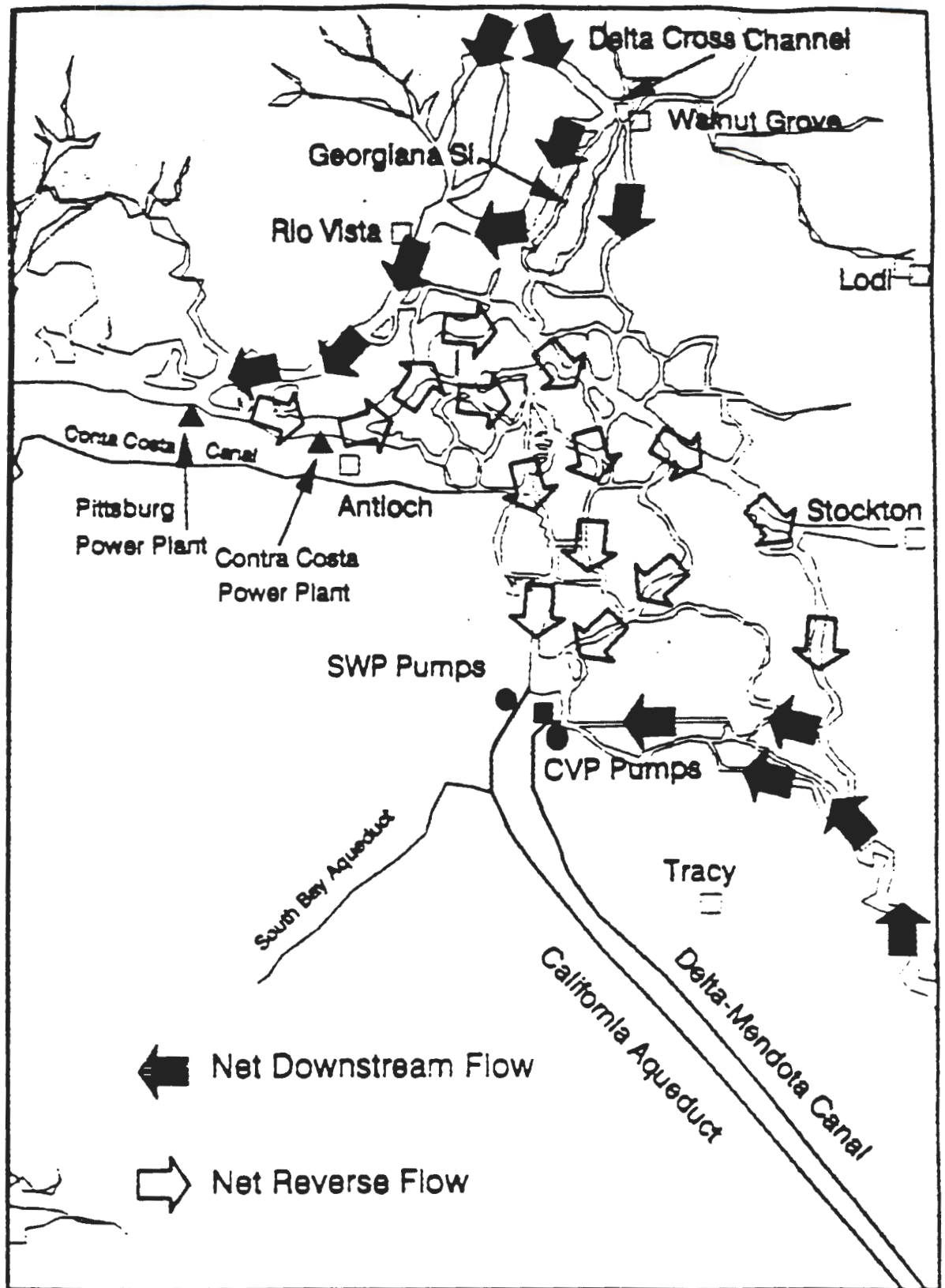
64

Figure 19. Typical summer flow patterns in the Sacramento-San Joaquin Delta. CVP-SWP export pumping has changed the natural flow patterns. Reverse flows transport many delta smelt from their nursery to the CVP-SWP diversions in the south Delta.
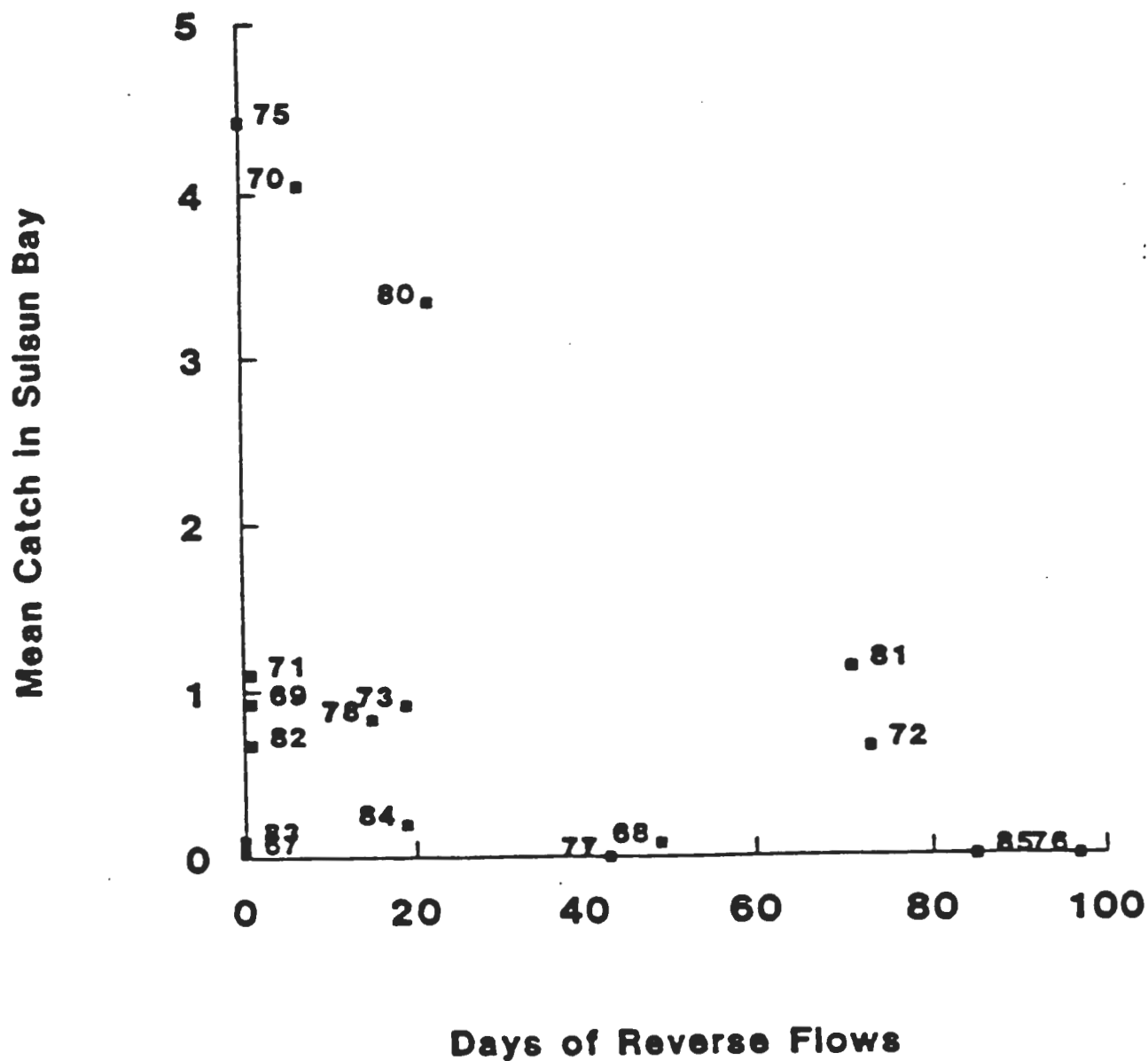
Figure 20. Mean Densities of fall populations of Delta smelt in Suisun Bay vs. numbers of days of reverse flows in the San Joaquin River during March to June. From Moyle and Herbold (1989).

Such, an association between reverse flows and smelt abundance is conceptually reasonable although it may, at least partly, reflect other correlated impacts of low river inflows or outflows. The sometimes low abundance indices at low reverse flows and the lack of association between reverse flows and smelt since 1983 indicate that reverse flows are not the sole mechanism driving the delta smelt population. A plot using the total population index is similar to that for the Suisun Bay portion, except for 1972 when delta smelt abundance was high despite 72 days of reverse flows during March-June (Figure 21).

Even when the net flow of the lower San Joaquin River is not reversed, net flow usually is still reversed in the southern Delta; thus, deltawide, there is dispersal of fish associated with the ever changing tides which maintains their exposure to entrainment by the CVP and SWP. The reverse flow of the southern Delta draws young fish and their food organisms out of the spawning and nursery areas to the north and transports them to the diversion sites.

The louver screens in front of the SWP and CVP pumps guide many of the young fish to holding tanks and tank trucks in which they are transported back to the western Delta and released. However, numerous fish, particularly larvae and others too small to swim well, pass through the screens and are lost into the aqueduct

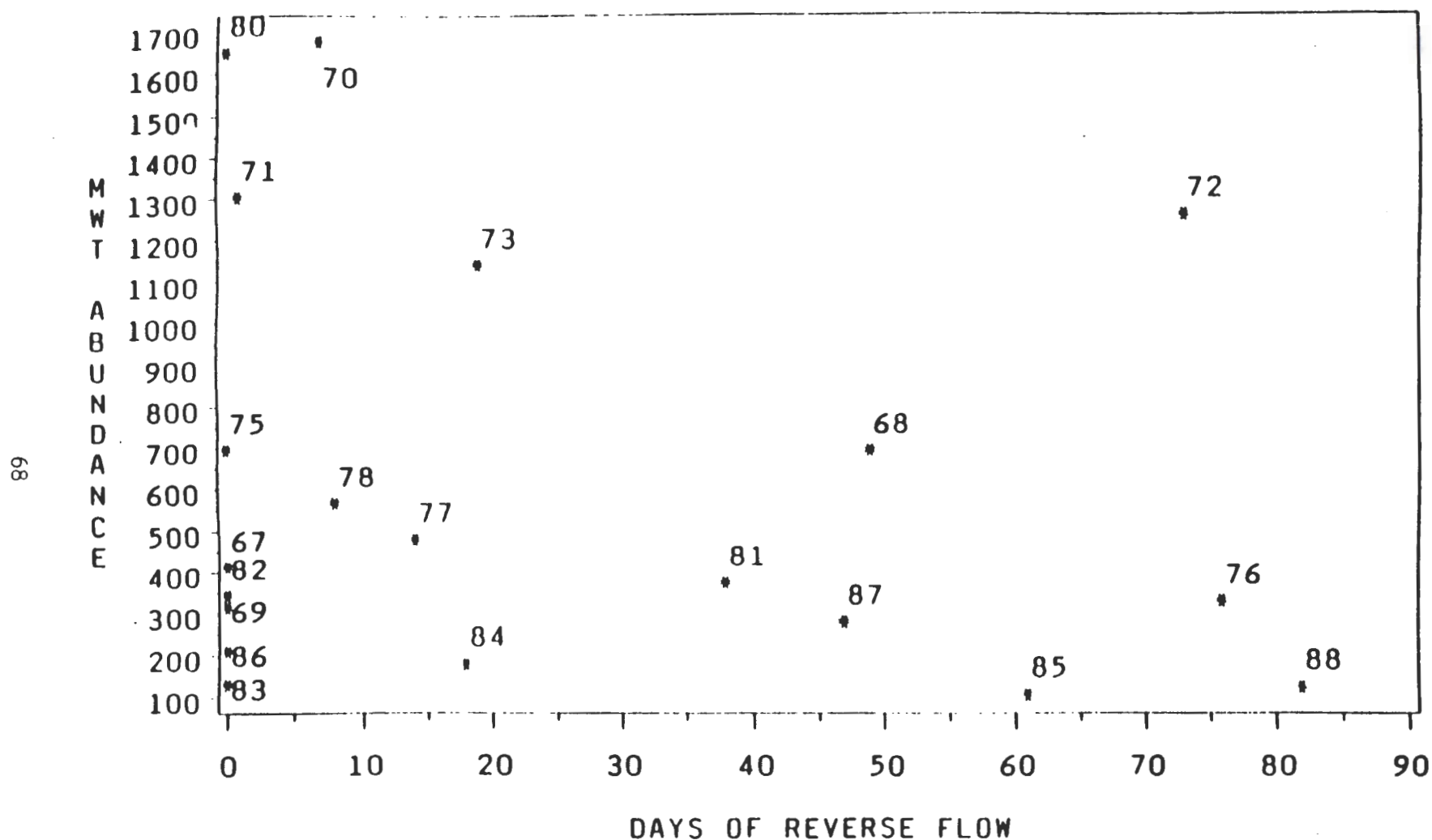ABUNDANCE VS NUMBER DAYS OF MARCH-JUNE REVERSE FLOW

Figure 21. Relationship between fall midwater trawl index of delta smelt abundance and the number of days of reverse flows in the Lower San Joaquin River from March to June.

system. Substantial numbers of the many young delta smelt that are salvaged (pages 31 to 41) also die due to stresses received during the handling and trucking. Others are eaten by larger fish in the SWP's Clifton Court Forebay and near the trash racks at both the CVP and SWP screens. These factors have not been evaluated for delta smelt but are known to be significant detriments to striped bass (DFG 1987).

Delta smelt are most vulnerable to entrainment during spring and summer as shown by the number salvaged per-acre-foot of exports by the SWP (Figure 22). This pattern reflects the late winter-spring spawning season and growth and mortality of young fish. During April and May, abundance of young smelt at the SWP and CVP diversions probably is greater than shown in Figure 22. However, this tendency is not displayed by the salvage estimates because the smelt are so small that they pass through the screens and are not salvaged during the first month or two of life. Also, smaller smelt are not readily identifiable by the technicians responsible for sampling salvaged fish.

The intra-year salvage pattern in 1977-1978 was a notable exception to the typical pattern. Through much of 1977, water exports were reduced, due to a major drought, and while a delta smelt salvage peak occurred in July, the greatest entrainment and salvage of the 1977 year class occurred from December 1977
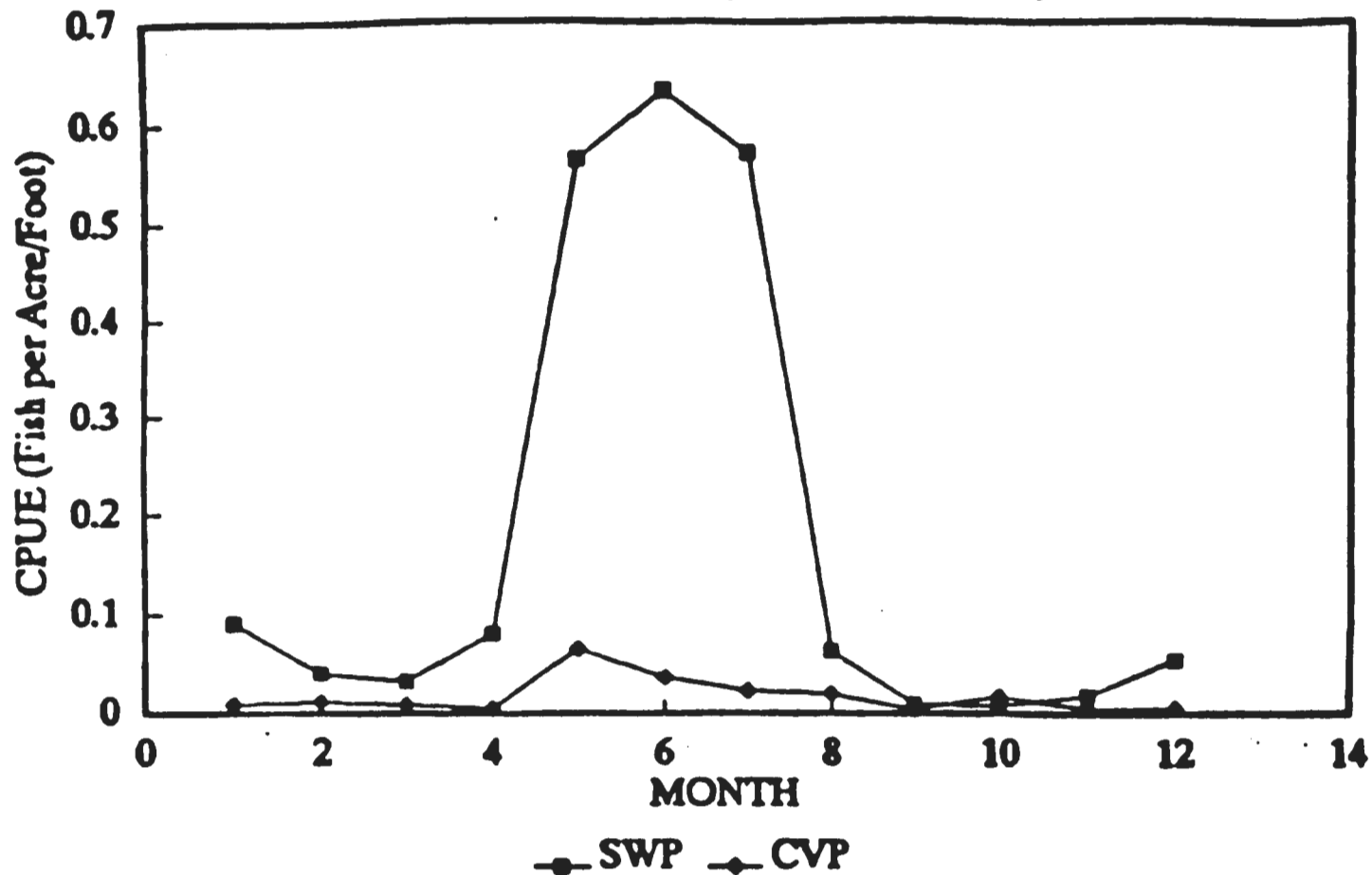
Figure 22. Mean monthly salvage of delta smelt per acre foot of water diverted by the State Water Project and Central Valley Project.

through February 1978 when water exports increased after the drought broke (Table 15). In fact, the salvage of 134,000 delta smelt at the SWP in January 1978 almost equaled the total for allof 1977 (146,000 fish) and exceeds the annual totals for all subsequent years.

What is the importance of entrainment losses with respect to the population decline of delta smelt? This is unclear. Comparisons of estimated population levels (Table 13) and salvage estimates (Figures 4, 8 and 9) suggest entrainment losses potentially could cause major reductions in delta smelt abundance. The greatest annual salvage, and probably losses, to water project diversions occurred from 1970 to 1976 (Figure 8). Considering that few delta smelt live beyond 1 year, if such entrainment depleted the population, the impact should be noticeable the following year. Yet the population apparently did not crash until 1983, 13 years after 1970, the initial year of record with a major salvage. Also, looking at the salvage data alone, one might hypothesize that the unusual entrainment of maturing adults in 1977-1978 had critically depleted the stock, but again this hypothesis is inconsistent with the population trend depicted by the more comprehensive trawl and townet survey indices.

Nevertheless, delta smelt are ecologically similar to young striped bass which have been severely impacted by water

Table 15. Estimated Salvage of Delta Smelt and Water Exports at
the State Water Project diversion in the southern
delta, during 1977-1978.

	Month	Delta Smelt Salvage	Exports (thou. acre ft)
1977	Jan	6980	205
	Feb	2430	106
	Mar	1707	97
	Apr	2975	14
	May	3017	68
	Jun	3033	17
	Jul	43489	20
	Aug	6435	15
	Sep	17890	9
	Oct	2528	8
	Nov	350	51
	Dec	55101	224
1978	Jan	134089	365
	Feb	53960	343
	Mar	4217	108
	Apr	130	35
	May	3523	59
	Jun	36289	201
	Jul	1034	211
	Aug	2658	246
	Sep	244	211
	Oct	60	127
	Nov	473	131
	Dec	900	169

diversions (CDFG 1987, Stevens et al. MS.). Delta smelt are vulnerable to diversions throughout their life cycle, particularly in dry years, when they are concentrated in the Delta from which the water is diverted. Thus, even if water diversions were not directly responsible for the delta smelt population decline, their drain on the population may be a significant factor inhibiting recovery.

Toxic Substances

Dr. Moyle's petition points out that the Estuary receives a variety of toxic substances, including agricultural pesticides, heavy metals, and other products of our urbanized society. The effects of these compounds on delta smelt have never been tested, and their effects on fishes in general are poorly understood. Some of these substances are known to occur in the Estuary's fishes at levels that may inhibit their reproduction (Jung et. al 1984) or are sufficient to trigger health warnings (e.g. Mercury in striped bass) regarding human consumption. Also, recent bioassays by the Central Valley Regional Water Quality Control Board (Foe 1989) suggest that water in the Sacramento River is, at times, toxic to larvae of the fathead minnow, a standard EPA test organism . However, the timing of the delta smelt decline is not consistent with the increased, mid-to late-1970s, use of the chemicals thought to cause mortality in these bioassays.

Although there is no direct evidence of delta smelt suffering direct mortality or stress from toxic substances, this factor obviously cannot be eliminated as a potential agent adversely affecting the delta smelt population.

Flows Out of Optimal Range

Moyle and Herbold (1989) point out that the years of the major smelt decline have been characterized by not only unusually dry years with exceptionally low outflows (1987, 1988), but also by unusually wet years with exceptionally high outflows (1983, 1986). They suggest that moderately high flows are most beneficial in that they cause the primary delta smelt nursery area, which is the mixing zone of the Estuary, where outflowing freshwater meets incoming tidal water, to be located in Suisun Bay. Moyle and Herbold developed a complex analysis which suggests high productivity (as reflected in phytoplankton and zooplankton abundance) in the mixing zone is one of the strongest determinants of delta smelt abundance. This high productivity is associated with the establishment of the mixing zone in the shallow water of Suisun Bay. Thus, they suggest moderately high outflows are important in that food becomes more available for larval smelt than when outflows are extremely high or too low. Higher and lower outflows place the mixing zone and nursery too far downstream or upstream. Low outflows also are detriments in that the delta smelt population concentrates in the Delta portion

74

of the Estuary where they are most vulnerable to becoming entrained in water diversions.

Moyle and Herbold's thesis is logical; however, it is not entirely supported by the abundance indices that we have described. For example in 1972, the fall midwater trawl index was quite high despite low outflows and a levee break on Andrus Island drawing the mixing zone well into the Delta during June. Also, relatively high summer townet survey indices suggest early survival of delta smelt larvae was high during the drought of 1976 and 1977. Subsequent survival of these year classes appeared to be low, however. Furthermore, our multiple regression analysis (pages 56 to 59) did not indicate that delta smelt abundance is controlled by delta outflows.

Figure 23 illustrates the best relationship (selected from R^2 values after running all possible 2 consecutive monthly subsets from February to June) between the fall midwater trawl abundance index, delta outflow, and delta outflow^2. As explained previously, the outflow^2 term allows the regression predictions to decline if smelt abundance peaks at moderate flows and declines at high flows. Again, there is no evidence that outflow has had major effects on delta smelt abundance.
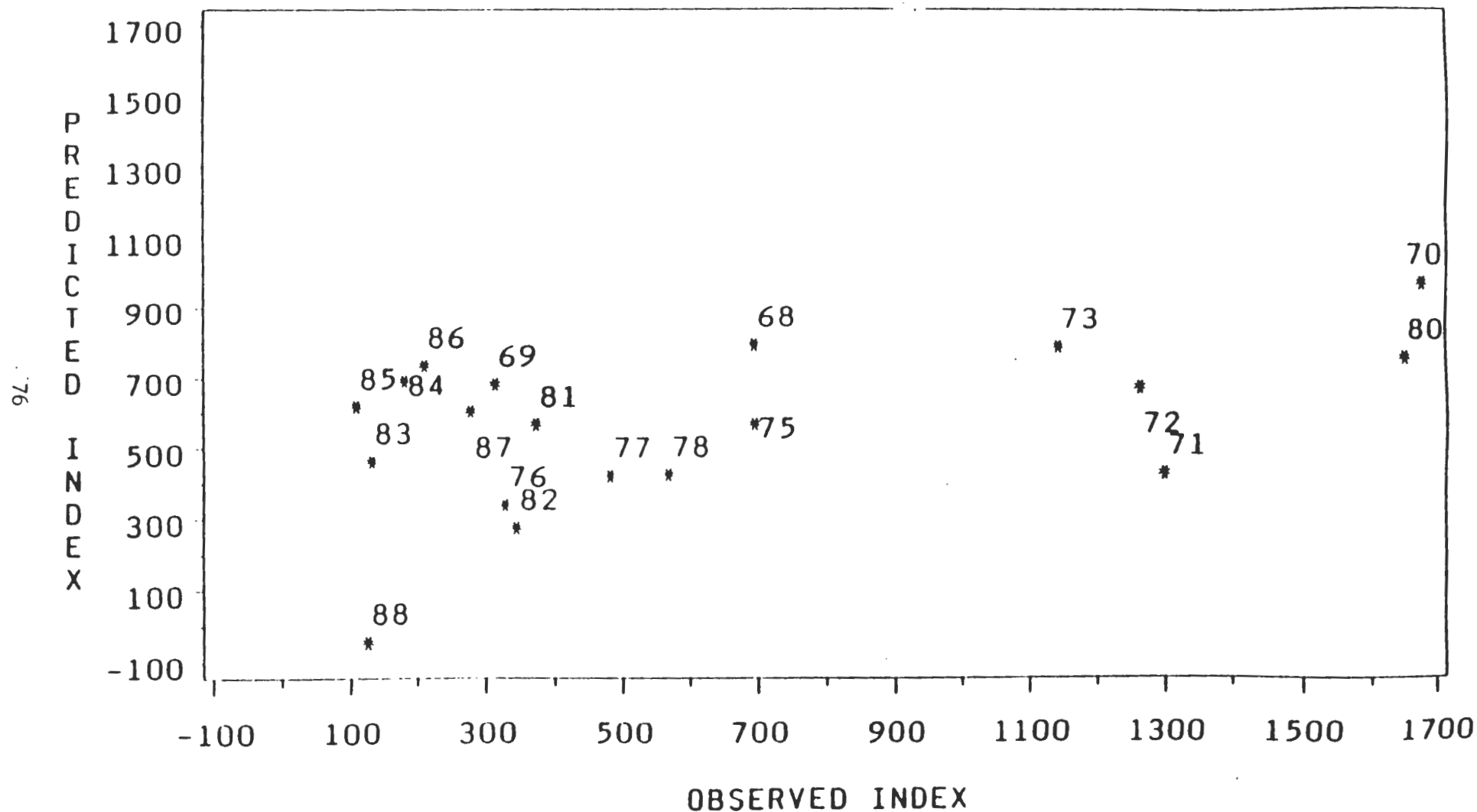
Figure 23. Relationship of midwater trawl observed abundance
indices and those predicted by the equation:
$-2635.7 + 1347.26$ (Log_{10} mean February-March Delta
outflow) -146.9 (Log_{10} mean March-April Delta
outflow)^2. $R^2 = 0.22$.

Notably, the recent series of very weak year classes began in 1983 which had a record sustained period of high spring outflows. That year, a substantial portion of the year class likely was washed far beyond Suisun Bay and perhaps entirely out of the Estuary.

Genetic Dilution

The closely related wagasaki, or Japanese smelt, was introduced in 1959 by the Department of Fish and Game into six California lakes and reservoirs: Dodge Reservoir (Lassen County), Dwinnell Reservoir (Siskiyou County), Freshwater Lagoon (Humboldt County), Spaulding Reservoir (Nevada County), Sly Park Reservoir (El Dorado County) and Big Bear Lake (San Bernardino County) (Wales 1962). They have subsequently been introduced into other reservoirs, including Shastina Reservoir (Siskiyou County) and Almanor Reservoir (Plumas County) (Moyle 1974, Moyle and Herbold 1989). Although the status of the introduced populations is uncertain, the potential exists for this fish to appear anywhere in the lower Klamath River system, the Sacramento River system, and possibly other systems as well (Moyle 1974). Wagasaki were collected from Folsom Reservoir (El Dorado County) by Department biologists in 1989 (D.P. Lee, Associate Fishery Biologist, CDFG, pers. comm.).

The wagasaki may hybridize with Delta smelt, but whether they have is not known, nor is it known if such hybridization could have a negative effect on the fitness of the Delta smelt. Thus, the threat of loss of genetic integrity or the possibility that the wagasaki could displace the Delta smelt completely through introgression or direct competition (Moyle and Herbold 1989) should be considered as speculative.

Exotic Species

Since the early 1970s, several exotic species, including both fish and invertebrates, have been accidentally introduced into the Sacramento-San Joaquin Estuary and become firmly established. A fish, the inland silverside (Menidia berylina), similar in size and food requirements to delta smelt, entered the Estuary in 1975 (Meinz and Mecum 1977) after flood flows transported it to the Delta from Clear Lake where it was intentionally, but illegally, introduced in 1967 (Fisher 1973). The invertebrate introductions have occurred through the discharge of organisms carried in ballast water of ships. The exotic invertebrates have included, since 1978, four species of zooplankton, all copepods (Sinocalanus doerii, Limnoithona sinensis, Oithona davisae, and Pseudodiaptomus forbesi); an amphipod (Lagunogammarus sp.); and a clam (P. amurensis). All of these invertebrates are of Asian origin. Some of these exotic species invasions and their

population explosions occurred before, others occurred after, but none coincide with the delta smelt decline.

Of the exotic copepods, S. doerii (established 1978) and P. forbesi (established 1986) have become particularly abundant. S. doerii apparently is rarely eaten by delta smelt; however, P. forbesi is now a major part of their diet. Laboratory experiments (Meng and Orsi, University of California, Davis and CDFG, respectively) have shown that larval striped bass readily take P. forbesi, but have difficulty capturing S. doerii. Apparently, the same is true for delta smelt. Potentially, the establishment of P. forbesi should compensate for the substantial decline in E. affinis which occurred during 1988 and 1989. However, since P. forbesi's annual cycle is such that it does not become abundant until summer, it is not readily available for the initial feeding of young smelt during the spring. Circumstantial evidence, from field monitoring and some sketchy laboratory experiments, suggests that filtering by the clam, P. amurensis, may have caused the decline in E. affinis which, historically, was available to delta smelt during their early nursery period. While this decline in E. affinis occurred after the decline in delta smelt, its near absence, possibly caused by the exotic, P. amurensis, may inhibit the smelt's recovery.

Disease and Parasites

Diseases and parasites of delta smelt have never been studied;
thus, there is no evidence concerning their role in the
population decline. General studies on parasites of Delta
fishes, however, have found numerous protozoans, worms
(trematodes, cestodes, nematodes, etc.) and crustaceans which
have affected at least 28 species of fish (Edwards and Nahhas
1968, Hensley and Nahhas 1975). Striped bass in the Delta are
more heavily infested with parasites than Atlantic coast striped
bass, perhaps indicating that the Delta environment may be
degraded by toxicants or pollutants to the point that resistance
to parasites in resident fishes is weakened (CDFG 1989). Also,
widespread sightings of dead fish suggest that, in some years,
disease outbreaks have caused mass mortalities of carp (Cyprinus
carpio) and white catfish (Ictalurus catus) in California's
Central Valley including the Delta. If disease or parasites are
important or should they become important, they certainly could
prevent the recovery of delta smelt from current population
levels.

Competition and Predation

Delta smelt evolved with native predators such as squawfish
(Ptychocheilus grandis), Sacramento perch (Archoplites
interruptus), and steelhead (Oncorhynchus mykiss); however,

predation by these species, none of which is currently abundant in the Estuary, is unlikely to be responsible for the relatively recent decline observed in Delta smelt. Striped bass, which were introduced in 1879, have been the most abundant predator (adults and sub-adults) and competitor (young) in the portion of the Estuary inhabited by Delta smelt, but striped bass also have suffered a serious decline which began in the 1970s and preceded the decline in delta smelt. Also, abundance indices for several other potential predators or competitors did not exhibit increases that could account for reduced delta smelt abundance (Figure 24). In fact, several of those potential competitors or predators--longfin smelt, threadfin shad and white catfish--also show signs of population erosion approximately coinciding with, or, in the case of white catfish, preceding the decline of delta smelt.

In essence, there just has not been a consistent increase in the abundance of any potential predator or competitor that could account for the decline of delta smelt.

Drs. Moyle and Herbold (1989) suggest that the Department's effort to enhance the Sacramento-San Joaquin striped bass population through the stocking of hatchery-reared fish could cause excessive predation on delta smelt. Striped bass are highly pisciverous (eat other fish); however, comprehensive striped bass food habit studies (Stevens 1966, Thomas 1967)
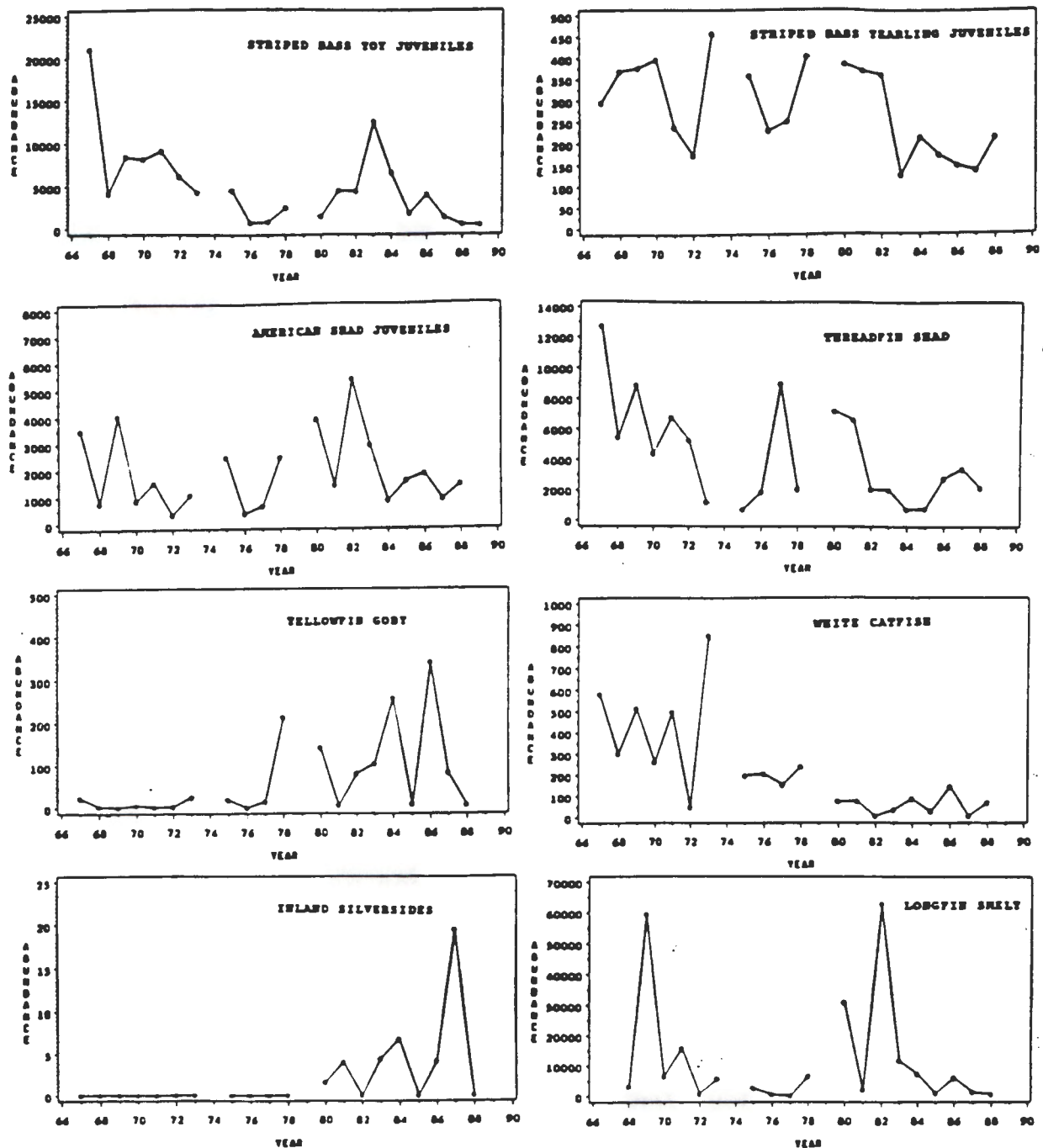
81

Figure 24. Trends in midwater trawl abundance indices of
potential competitors or predators of delta smelt.
These abundances have either decreased or been stable
coincident with the period of decline in Delta smelt
except for the yellowfin goby which generally has been
more abundant. There were no trawl surveys in 1974
and 1979.

indicated that, while delta smelt were occasionally consumed, they were not a significant prey of striped bass even in the early 1960s when delta smelt and striped bass were both much more abundant. Thomas (1967) notes that several potential prey species, including delta smelt, were less abundant in the striped bass diet than expected based on their abundance in the environment. Factors which reduce the availability of delta smelt and certain other species to striped bass are not understood.

Thus, while competition and predation cannot be ruled out as threats to delta smelt, the available evidence suggests that they are not a major threat.

CONCLUSIONS

We have examined several measures of delta smelt abundance; all indicate that the population has declined, although these measures are not consistent in their depiction of the timing and magnitude of the decline. The best measures, based on the summer townet and fall midwater trawl surveys, indicate that delta smelt abundance consistently has been lower since 1983 than in previous years. Based on the midwater trawl survey, the average population since 1983 (index of 175) has only been about one-

fifth of the average population level (index of 861) from 1967 to
1982, and one-tenth of the peak level (index of 1840) in 1980.
Delta smelt abundance has been highly variable over the period of
record. Our evaluation of factors potentially affecting delta
smelt abundance did not point strongly to any particular cause of
this variability or the sustained population decline since 1983.
However, failure to identify factors regulating the population
does not mean the tested factors are not important. Such failure
may simply reflect sampling associated variability in our
measures of delta smelt abundance and/or the environment.

The Fish and Game Commission is guided by the State Endangered
Species Act and the guidelines promulgated under this Act in
determining whether a species may be properly listed as
endangered or threatened. Section 670.1(b) of Title 14 of the
California Code of Regulations sets forth the listing criteria.
Under this section, the Commission may list a species if it finds
that its continued existence is in serious danger, or is
threatened by any of the following factors.

- ° Present or threatened modification or destruction of
    its habitat;
- ° overexploitation;
- ° predation;
- ° competition;

°   disease; or

°   other natural occurrences or human-related activities.

To meet the State Endangered Species Act's definition of "endangered", a species must be:

(1)   a native species or subspecies;

(2)   a bird, mammal, fish, amphibian, reptile or plant;

(3)   in serious danger of becoming extinct throughout all, or a significant portion, of its range;

(4)   affected by loss of habitat, change in habitat, overexploitation, predation, competition, or disease (Cal. Fish and Game Code Sec. 2062).

A "threatened" species is a species which is "likely to become an endangered species in the foreseeable future" in the absence of the special protection provided by the Act. (Sec. 2067). The Fish and Game Code (Sec. 2072.3) lists additional factors relevant to a determination that a species is threatened or endangered:

°   population trend;

°   range;

°   distribution;

°   abundance;

°   life history;

° ability to survive and reproduce;

° degree and immediacy of threat;

° existing management efforts;

° type of habitat.

Dr. Moyle's petition declares: "The Delta smelt fits the
definition of an endangered species as it is in danger of
extinction throughout its entire limited range. It is vulnerable
to extinction because (1) it is short-lived, (2) it has
relatively low fecundity, (3) it is a planktivore throughout its
life cycle, and (4) it is confined to the upper Sacramento-San
Joaquin estuary." Our analysis indicates that declarations (1)-
(4) are true. Additionally, introductions of exotic organisms
have altered the delta smelt's food supply, and water projects
have adversely modified the delta smelt's habitat, distribution
and probably abundance within the Estuary. While our analysis
failed to determine the specific relationships between these
threats and the smelt population, that is not crucial to
determining whether delta smelt should be listed as threatened or
endangered.

Major adverse habitat modifications include effects of changes in
the character and position of the salinity gradient and
exploitation through entrainment in diversions. Such population
threats are likely to worsen or, at best, remain stable (Table
16). Trends in abundance of other species, such as striped bass,

Table 16.   Probable Trend in Delta Smelt Population Threats.
            W = worse, S = Stable

Threat	Trend
Inadequate Food Supply	S
Inadequate spawning stock	S or W
Entrainment Losses	W
Toxicity	?
Delta outflows	W
Genetic dilution	S
Exotic introductions	S (if ship ballast discharges are controlled), W (if ship ballast discharges are not controlled)
Disease and parasites	S or W

also point toward a general degradation of the delta smelt's habitat.

Thus, the delta smelt population trend, certain life history attributes, and environmental threats tend to support "listing". The most relevant issue, however, is whether the population is low enough that it is in danger of extinction. The scientific information is insufficient to make that determination. Unfortunately, it is a very complicated scientific determination, and no scientific study which we might implement will provide a conclusive answer in the next few years. Meanwhile the population might become extinct.

The Department of Fish and Game believes that the relatively stable, albeit low, population is not in imminent danger of extinction. One factor supporting this contention is that the population has historically rebounded quickly from levels nearly as low as present ones. While we cannot be certain that such rebounds will not happen again, the persistent low populations since 1983, the nature of the delta smelt's life history and distribution, and increasing threats to its habitat lead us to conclude that the delta smelt may well "become an endangered species in the forseeable future". Hence, based on the best scientific information available (Section 2074.6 CESA), the

Department believes that the most prudent action is to list the delta smelt as a Threatened Species.

RECOMMENDATIONS

Petitioned Action

1. The Commission should find that the petitioned action that is warranted is for the status of State Threatened.
2. The Commission should publish notice of its intent to amend Title 14 CCR 670.5 to add the delta smelt (Hypomesus transpacificus) to its list of Threatened and Endangered Species.

Recovery and Management Actions

The Department's objective is the protection of a sufficient number of delta smelt to insure their long-term survival in their native habitat and range. In order to achieve recovery, the population must be protected, monitored, and shown to be self-sustaining. Annual monitoring and evaluation should be increased after input from interested parties. Recovery goals and reclassification criteria need to be established. When recovery goals have been met, the Department will make recommendations to the Commission regarding delisting this species.

89

The following actions have potential to achieve management and
recovery objectives.

1. Improve species identification and fish handling procedures
    at the existing State and Federal Water Project diversions
    from the Delta. Such actions could reduce present
    entrainment losses to these major diversions.

2. Modify pumping strategies at the State and Federal Water
    project diversions to reduce entrainment losses during
    periods when delta smelt are most abundant.

3. Increase spring and summer delta outflows to maintain the
    entrapment zone and major delta smelt nursery in the Suisun
    Bay region where food supplies are greater than in the Delta
    and exposure to diversions is minimal.

4. Support regulations restricting ship ballast water
    discharges to eliminate or minimize new introductions of
    potentially harmful exotic species. S 2244 and HR 4214
    currently being considered by the U.S. Congress would create
    such regulations.

5. Evaluate losses to agricultural diversions in the Delta.
    Screening these diversions probably would reduce entrainment
    and losses to local crop irrigation.

6. Remove water project diversions from the Delta. Moving the diversion intakes to the Sacramento River upstream from the major nursery area would do this and also provide benefits to other species which formerly made more use of the Delta.

7. Consider developing pond culture techniques for the purpose of creating "refuge" populations.

Alternatives to the Petititioned Action

If the Commission should choose not to list the Delta smelt, it is our opinion that this fish would be deprived of protection provided through recognition and formal consultation available to a listed species. When a species is listed as Threatened or Endangered, a higher degree of urgency is mandated, and protection and recovery receives more attention from the Department and other agencies than does a non-listed species.

In the absence of listing, it still would be possible to devise a management plan for this species. However, this Departmental status review indicates that the future existence of this species is already seriously threatened. Despite good intentions on the part of the Department and the Commission, promises of management and protection for a non-listed species do not have the weight of law behind them, and thus seldom receive high priority in the

91

eyes of other agencies. Without the benefits of listing and the cooperation of other agencies in preservation and recovery actions, the species could decline further until the population is no longer viable, and is no longer able to exist in perpetuity. Eventually, extinction could occur.

Although the petitioner has requested listing of the Delta smelt as Endangered, the Department has made the recommendation and the Commission has the option to list this fish as Threatened instead. Under this option, the Delta smelt would receive the same special consideration and protection under CESA and the California Environmental Quality Act (CEQA) as if it were listed as Endangered. This Departmental status review indicates that the continued existence of the Delta smelt is seriously threatened throughout its range, and that this alternative is appropriate.

PROTECTION AFFORDED BY LISTING

If listed, the Delta smelt will receive protection from take during development activities subject to CEQA and will be subject to formal consultation requirements under CESA. The species will also be eligible for the allocation of resources by government agencies to provide protection and recovery. During the CEQA environmental review process, listed species receive special

consideration, and protection and mitigation measures can be implemented as terms of project approval. Species that are not listed do not readily receive protection. The status of listing provides a species with recognition by lead agencies and the public, and significantly greater consideration is given to the Department's recommendations resulting from project environmental review.

Listing this species increases the likelihood that State and Federal land and resource management agencies will allocate funds and personnel for protection and recovery actions that benefit the Delta smelt. With limited funding and a growing list of Threatened and Endangered species, priority has been and will continue to be given to species that are listed. Those that are not listed, although considered to be of concern, are rarely given serious consideration under these circumstances.

ECONOMIC CONSIDERATIONS

The Department is not required to prepare an analysis of economic impacts per CESA Section 2074.6. The Department is to provide a report to the Commission "based upon the best scientific information available to the Department, which indicates whether the petitioned action is warranted, which includes a preliminary identification of the habitat that may be essential to continued

existence of the species, and which recommends management
activities and other recommendations for recovery of the
species".

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TABLE OF CONTENTS

Report to the Fish and Game Commission:

A Status Review of the

Delta Smelt (<u>Hypomesus</u> <u>transpacificus</u>)

in California[1]

EXECUTIVE SUMMARY

This report was prepared in response to a petition received by
the Fish and Game Commission from Dr. Peter B. Moyle of the
University of California at Davis to list the Delta smelt
(<u>Hypomesus</u> <u>transpacificus</u>) as an Endangered Species under the
authority of the California Endangered Species Act (Fish and Game
Code Sections 2050 et seq.).

On August 23, 1989, pursuant to the Section 2074.2 of the
California Endangered Species Act (CESA), the Commission
determined that the petition contained sufficient information to
indicate that the petitioned action may be warranted. Pursuant
to Section 2074.6 of CESA, the Department undertook a review of
this petition. Based on the best scientific information
available on the Delta smelt, the Department has evaluated
whether, in fact, the petitioned action should be taken.
Information and comments on the petitioned action and the Delta

[1] Prepared August 1990.

iii

smelt were solicited from interested parties, management
agencies, and the scientific community.

This report presents the results of our review and analysis.

Findings

The Delta smelt is a small fish endemic to the Sacramento-San
Joaquin Estuary. Delta smelt are euryhaline and much of the year
are typically most abundant in the entrapment zone, where
incoming saltwater and outflowing freshwater mix. This species
feeds exclusively on zooplankton, spawns in freshwater, and
usually only lives for one year.

Information from six different data sets all indicate that the
population of Delta smelt has declined. The best measures, based
on the summer townet and fall midwater trawl surveys, indicate
that abundance of this species has been consistently low since
1983. Based on the midwater trawl survey, the average population
since 1983 has been only about one-fifth of the average
population level from 1967 to 1982, and one-tenth of the peak
level in 1980.

Conclusions

Although the petitioner requested that the species be listed as
endangered, the Department finds that the Delta smelt should be

listed as a threatened species, based on Section 670.1(b) of
Title 14 of the California Code of Regulations and Section 2072.3
of the Fish and Game Code. The Department's findings are based
on the following:

1. The recent decline in the copepod, _Eurytemora affinis_, a
    major diet component of the Delta smelt, must be considered
    as a potential threat to the smelt's recovery unless other
    food resources compensate or this copepod recovers to its
    former abundance.

2. Although spawning stock abundance may not have been an
    important factor in Delta smelt year class success in the
    past, present or future low stock levels may inhibit the
    potential for population recovery. The relatively low
    fecundity of this species and its planktonic larvae, which
    undoubtedly incur high rates of mortality, indicate that
    year class success of the Delta smelt must depend on
    reproduction by fairly large numbers of fish.

3. The relationship between Delta smelt abundance and water
    diversions is not clear. Delta smelt are ecologically
    similar to young striped bass which have been severely
    impacted by water diversions. Whether or not water
    diversions are directly responsible for the Delta smelt

population decline, their drain on the population may be a
significant factor inhibiting recovery.

4.   Although there is no direct evidence of Delta smelt
suffering direct mortality or stress from toxic substances,
such substances cannot be eliminated as having adverse
effects on the population.

5.   There is no evidence that Delta outflow has had major
effects on Delta smelt abundance.

6.   No research has been done to determine if the wagasaki, a
closely related species introduced into several reservoirs
in the Delta drainage, hybridizes with or competes directly
with the Delta smelt.

7.   A number of exotic fish and invertebrate species have been
introduced into the Sacramento-San Joaquin Estuary.
Although none of these species can be directly linked to the
decline in Delta smelt, their presence may inhibit the
smelt's recovery.

8.   Diseases and parasites of Delta smelt have never been
studied; thus, there is no evidence concerning their role in
the population decline. Should they be important, they

could prevent the recovery of Delta smelt from current low population levels.

9. Although competition and predation cannot be ruled out as threats to Delta smelt, the available evidence suggest that they are not a major threat. In fact, several potential competitors or predators also show signs of population erosion approximately coinciding with or preceding the decline of Delta smelt.

10. The Delta smelt population trend, certain life history attributes, and environmental threats tend to support listing. The scientific information is insufficient, however, to determine whether the population is low enough that it is in imminent danger of extinction. This is a complicated scientific determination, and no study which might be implemented will provide a conclusive answer in the next few years. Meanwhile, the population might become extinct. The most prudent action, therefore, is to list the Delta smelt as a threatened species.

Recommendations

Listing:

1. The Commission should find that the Delta smelt is a threatened species.

2. The Commission should publish notice of its intent to amend Title 14 CCR 670.5 to add the Delta smelt (_Hypomesus transpacificus_) to its list of Threatened and Endangered Species.

Management and recovery objectives:

1. Improve species identification and fish handling procedures at the existing State and Federal Water Project diversions from the Delta. Such actions could reduce present entrainment losses to these major diversions.

2. Modify pumping strategies at the State and Federal Water project diversions to reduce entrainment losses during periods when delta smelt are most abundant.

3. Increase spring and summer delta outflows to maintain the entrapment zone and major delta smelt nursery in the Suisun

Bay region where food supplies are greater that in the Delta and exposure to diversions is minimal.

4. Support regulations restricting ship ballast water discharges to eliminate or minimize new introductions of potentially harmful exotic species. S 2244 and HR 4214 currently being considered by the U.S. Congress would create such regulations.

5. Evaluate losses to agricultural diversions in the Delta. Screening these diversions probably would reduce entrainment and losses to local crop irrigation.

6. Remove water project diversions from the Delta. Moving the diversion intakes to the Sacramento River upstream from the major nursery area would do this and also provide benefits to other species which formerly made more use of the Delta.

7. Consider developing pond culture techniques for the purpose of creating "refuge" populations.

Public Responses

During the twelve month review period, the Department contacted a number of affected and interested parties, invited comment on the petition and our draft status review, and requested any

additional scientific information that may be available. A copy
of the Public Notice and a list of parties contacted are
contained in Appendix A. A summary of comments on the draft
status review is in Appendix B. Scientific comments will be
addressed as part of the regulatory proceedings should the
Commission find that the petition warrants action.

LIST OF TABLES

xv

State of California
The Resources Agency

DEPARTMENT OF FISH AND GAME

REPORT TO THE FISH AND GAME COMMISSION:

A STATUS REVIEW OF THE
DELTA SMELT (HYPOMESUS TRANSPACIFICUS)
IN CALIFORNIA

Prepared by

Donald E. Stevens
Fisheries Management Supervisor

Lee W. Miller
Associate Fishery Biologist

and

Betsy C. Bolster
Associate Fishery Biologist

Approved by

Harold K. Chadwick, Program Manager
Bay-Delta Project
and
Robert R. Rawstron, Chief
Inland Fisheries Division

August 1990

Candidate Species Status Report 90 - 2

APPENDIX A

Section 2074.4 of the Fish and Game Code requires the Department of Fish and game to notify affected and interested parties and landowners and to solicit data and comments on petitions accepted by the Fish and Game Commission. To fulfill this requirement, the Department sent notices and/or copies of the petition to the following persons and organizations. Legal notices were placed in the newspapers indicated below:

PERSONS/ORGS. RECEIVING DELTA SMELT PETITION AND/OR PUBLIC NOTICE

US Dept. of the Army
Sacramento District
Corps of Engineers
650 Capitol Mall
Sacramento, CA 95814-4794

Raymond E. Barsch, General Manager
State Reclamation Board
1416 Ninth Street, Room 455-6
Sacramento, CA 95814

Claire T. Dedrick, Exec. Officer
State Lands Commission
1807 13th Street
Sacramento, CA 95814

Tim Egan, President
California Waterfowl Assn.
3840 Rosin Court, Suite 200
Sacramento, CA 95834

Alan Pendleton, Exec. Director
SF Bay Conservation & Development
 Commission
30 Van Ness Ave., Suite 2011
San Francisco, CA 94102-6080

Monica Liquori, Exec. Director
Suisun Marsh Natural History Assn.
1171 Kellogg Street
Suisun, CA 94585

Peter Douglas, Exec. Director
California Coastal Commission
631 Howard Street
San Francisco, CA 94105

William H. Ivers, Director
Dept. of Boating and Waterways
1629 S Street
Sacramento, CA 95814

Peter Grenell, Executive Officer
State Coastal Conservancy
1330 Broadway, Suite 1100
Oakland, CA 94610

W. Don Maughan, Chairman
Water Resources Control Board
PO Box 100
Sacramento, CA 95801

Richard Spotts, Regional Rep.
Defenders of Wildlife
5604 Rosedale Way
Sacramento, CA 95822

Leland Lehman, President
Suisun Resource Conservation
 District
PO Box 426
Suisun, CA 94585

Rick Coleman
SF National Wildlife Refuge
PO Box 524
Newark, CA 94560

Huston Carlyle, Jr., Director
Office of Planning & Research
1400 10th Street
Sacramento, CA 95814

Orville Abbott, Exec. Officer
California Water Commission
1416 9th Street, Room 1104-4
Sacramento, CA 95814

Henry R. Agonia, Director
Dept. of Parks and Recreation
PO Box 942836
Sacramento, CA 94296-0001

David N. Kennedy, Director
Dept. of Water Resources
PO Box 942836
Sacramento, CA 94236-0001

Sacramento County
Board of Supervisors
700 H Street, Room 2450
Sacramento, CA 95814-1280

Bob McKay, President or
Elizabeth Wright, Exec. Secretary
California Wildlife Federation
1023 J Street, Suite 203
Sacramento, CA 95814

Sylvia McLaughlin, President
Save SF Bay Association
PO Box 925
Berkeley, CA 94701

Laurel Mayer, Vice President
The Nature Conservancy
Western Regional Office
785 Market Street, Third Floor
San Francisco, CA 94103

Lawrence Downing, President
Sierra Club
730 Polk Street
San Francisco, CA 94109

Richard Hubbard, Exec. Director
California Natural Res. Federation
2830 10th Street, Suite 4
Berkeley, CA 94710

Robert Nuzum, President
CA Assn. Resource Conservation Dist.
1072 Juanita Drive
Walnut Creek, CA 94595

Edward Hastey, State Director
Bureau of Land Management
Federal Office Bldg., Room E-2841
Sacramento, CA 95825

Department Chair
Dept. of Biological Sciences
CSU-Sacramento
6000 J Street
Sacramento, CA 95819

Contra Costa County
Board of Supervisors
651 Pine Street, Room 106
Martinez, CA 94553

Solano County
Board of Supervisors
Solano County Courthouse
Fairfield, CA 94533

Gerald Meral, Exec. Director
Planning & Conservation League
909 12th Street, Suite 203
Sacramento, CA 95814

Charles Sibley
Tiburon Center for Environ. Studies
SF State University
Box 855
Tiburon, CA 94920

Jerry Bogges, President
The Oceanic Society
SF Bay Chapter
Fort Mason center, Bldg. E
San Francisco, CA 94123

Sheila Byrne
Pacific Gas & Electric Company
TES/Moore Building
3400 Crow Canyon Road
San Ramon, CA 94583

Dr. John McCosker
California Academy of Sciences
Golden Gate Park
San Francisco, CA 94118

Michael Stroud, Head
Natural Resources Branch
US Dept. of the Navy, Western Div.
Nav. Facilities Eng. Command,
Code 243, PO Box 727
San Bruno, CA 94066

Rolf Wallenstrom, Reg. Director
US Fish and Wildlife Service
Northwest Regional Office
500 NE Multnomah St., Suite 1692
Portland, OR 97232

Dr. Paul Ehrlich
Center for Conservation Biology
Stanford University
Stanford, CA 93405

Director
Museum of Vertebrate Zoology
UC Berkeley
Berkeley, CA 94720

Dr. Peter Moyle
Wildlife and Fisheries Biology
UC Davis
Davis, CA 95616

Kenneth R. Boyd
American Water Works Association
PO Box 2108
Livermore, CA 94550

Daniel Phelan
Bay Area League of Industrial Assns
155 Jackson #305
San Francisco, CA 94111

Scott Hodley
Bay Institute of San Francisco
10 Liberty Ship Way #120
Sausalito, CA 94965

Greg Mannesto
US Army Corps of Engineers
650 Capitol Mall
Sacramento, CA 95814

Robert Helwick, Senior Attorney
East Bay MUD
2130 Adeline Street
Oakland, CA 94607

David Stewart
Water Management Division
Environmental Protection Agency
215 Fremont Street
San Francisco, CA 94105

Martin Seldon
Federation of Fly Fishermen
PO Box 2393
Sunnyvale, CA 94807-2393

Ron Davis
CA Municipal Utility Assn.
1225 8th Street, Suite 440
Sacramento, CA 95814

Dan Taylor
National Audubon Society
555 Audubon Place
Sacramento, CA 95825

Department Chair
Dept. of Biology/Nat Resources
UC Berkeley
Berkeley, CA 94720

William H. Geyer
Consulting/Advocacy in CA Gov't.
1029 K Street, Suite 33
Sacramento, CA 95814

Robert T. Cockburn
Bay Area Dischargers Association
2130 Adeline Street
Oakland, CA 94607

Steven McAdam
SF Bay Conservation/Development
 Commission
30 Van Ness Avenue
San Francisco, CA 94102

Austin Nelson
Contra Costa Water District
PO Box H20
Concord, CA 94524

Robert Baiocchi, Exec. Dir.
CA Sportfishing Protection Assn.
1859 Salider Way
Paradise, CA 95969

Thomas Graff
Environmental Defense Fund
5655 College Ave., Suite 304
Oakland, CA 94618

Don May
Friends of the Earth
2333 Elm Street
Long Beach, CA 90806

Ellen Johnck, Exec. Director
Bay Planning Coalition
666 Howard St., Suite 301
San Francisco, CA 94105

Association of Water Agencies
910 K Street, Suite 250
Sacramento, CA 95814-3577

Lori Smallwood-Wallack
CA Water Resources Association
1127 11th Street, Suite 602
Sacramento, CA 95814

Jane Darby, Water Chairperson
League of Women Voters of Redlands
309 Marcia Street
Redlands, CA 92373

Eric Johnson
Pacific Gas & Electric Company
3400 Crow Canyon Road
San Ramon, CA 94503

Mitch Ryan
Sen. John Garamendi's Office
State Capitol, Room 4081
Sacramento, CA 95814

John Coburn
State Water Contractors
555 Capitol Mall, Suite 575
Sacramento, CA 95814

John Beuttler
United Anglers of CA
2830 10th Street, Suite 4
Berkeley, CA 94710

Jim Arthur
US Bureau of Reclamation
2800 Cottage Way, Room 2137
Sacramento, CA 95825

Richard Oltman
US Geological Survey
2800 Cottage Way, Room W-2234
Sacramento, CA 95825

Laura King
Natural Resources Defense Council
90 New Montgomery, Suite 620
San Francisco, CA 94105

Bill Crooks, Executive Officer
Reg. Water Quality Control Board
3443 Routier Road
Sacramento, CA

Mike Valentine
State Lands Commission
1807 13th Street
Sacramento, CA 95814

Leo Winternitz
State Water Resources Control Board
Bay-Delta Program
901 P Street
Sacramento, CA 95814

Dr. Jack Williams
Fisheries Program Manager
US Bureau of Land Management
Division of Wildlife & Fisheries
18th and C Streets, NW
Washington, D.C. 20240

Martin Kjelson
US Fish and Wildlife Service
4001 Wilson Way
Stockton, CA 95205

Robert Hagan
Yolo Co. Flood Control & Water
 Conservation District
548 Oak Avenue
Davis, CA 95616

NEWSPAPERS WHICH PUBLISHED THE DELTA SMELT LEGAL NOTICE

Sacramento Bee
PO Box 15779
Sacramento, CA 95852

Fairfield Daily Republic
PO Box 47
Fairfield, CA 94533

San Francisco Chronicle
901 Mission Street
San Francisco, CA 94103

Contra Costa Times
PO Box 5088
Walnut Creek, CA 94596

Beginning June 22, 1990 the Department of Fish and Game circulated a draft report entitled "**Report to the Fish and Game Commission: A Status Review of the Delta Smelt (Hypomesus transpacificus) in California.**" This report was prepared in accordance with Section 2074.6 of the Fish and Game Code. The draft report was provided to the following individuals and organizations that responded to a November 27, 1989 public notice to other individuals and organizations that the Department identified as interested parties and to the general public. The distribution of the draft report provided an opportunity for public review and comment before the Department submitted a final report to the Fish and Game Commission and ensured that the Department had access to the best scientific information.

Ms. Betsy Bolster
Inland Fisheries Division
DFG - Region 2

Dr. Dennis Murphy
Dept. Biological Sciences
Stanford University

Mr. Keith Taniguchi
Office of Endangered Species
USFWS

Dr. Don Erman
Dept. Forestry and
Conservation
University of California,
Berkeley

Ms. Carla Markmann
Chair, Conservation Committee
American Fisheries Society

Mr. Peter Moyle
Dept. of Fish & Wildlife
University of California Davis

Mr. George R. Baumli
State Water Contractors
555 Capitol Mall Suite 575

Mr. Harold Meyer
Water Resources Management,
Inc.

Dr. Joe O'Connor
Aquatic Habitat Institute

Ms. Susan Joseph
Downey, Brand, Seymour and
Rohwer
555 Capitol Mall, 10th Floor

Mr. David Beringer
Division of Water Rights
Water Resources Control Board

Mr. David Anderson
Department of Water Resources
Office of the Counsel

State Clearing House

Mr. Randy Brown
Department of Water Resources
Central District

Mr. Ken Lentz
US Bureau of Reclamation

Mr. Chris Bowman
Sacramento Bee

Ms. Diana Jacobs
State Lands Commission

Mr. Phil Hogan
Soil Conservation Service

Mr. Robert Schaefer
Mr. Wil Tully
Bureau of Reclamation

Mr. John Merz
Sacramento River Preservation
Trust

Ms. Cay Goude
USFWS

Mr. Jim Canaday
Water Resources Control Board
Division of Water Rights

Mr. Barry Nelson
Save the Bay Association

Mr. William Davoren
Bay Institute of San Francisco

Mr. Robert Baiocchi
California Sportfishing
Alliance

Mr. John Beuttler
United Anglers

Mr. Al Jahns
Merron, Reid, Sheehy
801 K Street #2100
Sacramento, CA 95814

Mr. Scott Hadley
Bay Institute

Mr. Richard Spotts
Defenders of Wildlife

Dr. C. David Vanicek
Department of Biological
Sciences
CA State University -
Sacramento

Mr. Aaron King
Assemblyman Dan Hauser's
Office

Assemblyman William Campbell
State Capitol

Mr. Steven McAdam
San Francisco Bay Conservation
and Development Commission

Mr. Greg Mannesto
U.S. Army Corps of Engineers

Mr. Robert Helwick
Senior Attorney
East Bay Municipal District

Mr. Thomas Graff
Environmental Defense Fund

Mr. David Stewart
EPA
Water Management Division

Ms. Susan LeFever
Friends of the River

Ms. Ellen Johnck
Bay Planning Coalition

Mr. Ron Davis
CA Municipal Utility
Association

Mr. Gerald Meral
Planning and Conservation
League

Associations of CA Water
Agencies

Mr. Dan Taylor
National Audubon Society

Ms. Lori Smallwood
CA Water Resources Association

Ms. Jane Kay
San Francisco Examiner

Mr. Harold Gilliam
San Francisco Chronicle

Ms. Laura King
Natural Resources Defense
Council

Mr. Eric Johnson
Pacific Gas and Electric
Company

Mr. Bill Crooks
Regional Water Quality Control
Board

Mr. Dave Beringer
Bay-Delta Unit
Division of Water Rights

Mr. Jim Arthur
US Bureau of Reclamation

Mr. Richard Oltman
US Geological Survey

DEP'ARTMENT OF FISH AND GAME

1416 NINTH STREET
P.O. BOX 944209
SACRAMENTO, CALIFORNIA 95814-2090

November 27, 1989

PUBLIC NOTICE

TO WHOM IT MAY CONCERN:

Pursuant to Section 2074.4 of the California Fish and Game Code (FGC), **NOTICE IS HEREBY GIVEN** that on **August 29, 1989** the California Fish and Game Commission accepted a petition from **Dr. Peter Moyle** to amend the official State list of endangered and threatened species (Section 670.2, 670.5, Title 14, California Code of Regulations) as follows:

Species	Proposal
Delta smelt (Hypomesus transpacificus)	List as endangered
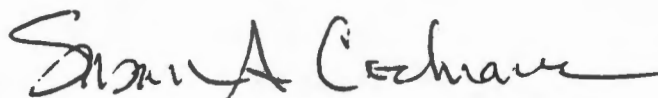
The California Endangered Species Act (FGC, Chapter 1.5, Section 2050 et seq.) requires that the Department of Fish and Game notify affected and interested parties that the Commission has accepted the petition for the purpose of receiving information and comments that will aid in evaluating the petition and determining whether or not the above proposal should be adopted by the Commission. If the above proposal includes adding a species to the list as endangered or threatened, the Commission's action has resulted in this species receiving the interim designation of "candidate species." The Department has 12 months to review the petition, evaluate the available information and report back to the Commission whether the petitioned action is warranted (FGC Section 2074.6). The Department's recommendation must be based on the best scientific information available to the Department. Therefore,

NOTICE IS FURTHER GIVEN that anyone with data or comments on the taxonomic status, ecology, biology, life history, management recommendations, distribution, abundance, threats, habitat that may be essential for the species or other factors related to the status of the above species, is hereby requested to provide such data or comments to:

> Natural Heritage Division
> California Department of Fish and Game
> 1416 Ninth Street, 12th Floor
> Sacramento, CA 95814

Responses received by **January 17, 1990** will be included in the Department's final report to the Fish and Game Commission. If the Department concludes that the petitioned action is warranted, it will recommend that the Commission adopt the above proposal. If the Department concludes that the petitioned action is not warranted, it will recommend that the Commission not adopt the proposal. (If the petitioned action is to list a species as endangered or threatened and the Commission accepts the Department's recommendation to not adopt the proposal, the species will lose its candidate status.) Following receipt of the Department's report, the Commission will allow a 45-day public comment period prior to taking any action on the Department's recommendation.

NOTICE IS FURTHER GIVEN that any species above proposed to be added to the State list as endangered or threatened is a "candidate species" pursuant to Section 2074.2 (FGC) and, pursuant to Section 2085 (FGC), may not be taken or possessed except as provided by Section 2080, et seq. of the FGC or other applicable statutes.

Susan A. Cochrane, Chief
Natural Heritage Division

(916) 324-8348

June 22, 1990

To Whom It May Concern:

The enclosed draft report represents the Department of Fish and
Game's analysis and response to a petition to list the Delta Smelt
as an endangered species. The Department has determined that the
Delta Smelt meets criteria set forth in the California Endangered
Species Act of 1984 for listing as a threatened species. This
draft report is being provided to all individuals and organizations
that responded to our public notices earlier in the review process.
We are providing another opportunity for the public to comment on
this matter before the Department transmits a final report to the
Fish and Game Commission for receipt at their August 3, 1990
meeting. Your comments must reach this office by July 18, 1990 to
be included in our final status report. The Commission will conduct
a hearing on the Departments recommendation and take public
testimony at their August 31, 1990 meeting in Sacramento.

Thank you for your interest in this matter.

                              Sincerely,
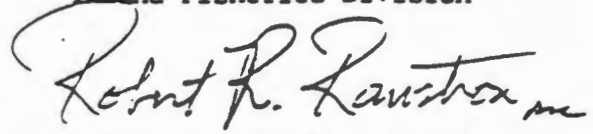
                              Susan A. Cochrane, Chief
                              Natural Heritagae Division

CALIFORNIA DEPARTMENT OF FISH AND GAME
NOTICE OF AVAILABILITY OF REPORTS

NOTICE IS HEREBY GIVEN that a draft report prepared by the Department of Fish and Game, pursuant to Section 2074.6 of the Fish and Game Code, in response to a petition to list the delta smelt (Hypomesus transpacificus) as an endangered species, is available for review and comment at the Natural Heritage Division Office, 1220 "S" Street, Sacramento, CA 95814, phone (916) 324-0561.

The Fish and Game Commission will receive the Department's final report at their August 3, 1990 meeting. The Commission will conduct a hearing on the Department's recommendation and take public testimony at their August 31, 1990 meeting in Sacramento.

<div align="right">
Department of Fish and Game
Inland Fisheries Division
</div>

June 29, 1990

<div align="right">
Robert R. Rawstron, Chief
</div>

Appendix B. Summary of Public Comments on Draft Status Review

A draft of this report was released on June 22 for public comment. The cover letter from Susan A. Cochrane, Chief Natural Heritage Division specified that comments must reach the Department by July 18, 1990 to be included in the final status report. Comments were received from the following individuals and organizations: 1) State Water Contractors (SWC), 2) McDonough, Holland and Allen, attorneys for Central Valley Project Water Association (CVPWA), 3) Downey, Brand, Seymour, and Rohwer (DBSR), attorneys representing more than twelve reclamation districts which siphon or pump water from delta channels, 4) California Central Valley Flood Control Association (CCVFCA), 5) The Planning and Conservation League (PCL), 6) Drs. Bruce Herbold and Peter Moyle (HM), 7) The Department of Water Resources (DWR), and 8) Dr. Dallas Weaver, Scientific Hatcheries (DW).

Concerns were expressed in the following general areas:

- adequacy of available information for purposes of depicting the delta smelt population trend and status (SWC, CVPWA),

- verification of the taxonomic status of the species (SWC, CVPWA),

- adequacy of data regarding the diet of delta smelt (SWC, CVPWA),

- resolution on the timing and distribution of spawning, mechanisms of larval transport, and reproductive potential (SWC, CVPWA),

- resolution on distribution within the Estuary (SWC, CVPWA),

- weak linkage between abundance and factors potentially controlling abundance (SWC, CVPWA, DWR),

- need for stronger technical foundation in support of listing and management recommendations (SWC, CVPWA, DWR),

- increased cost of water associated with screening agricultural diversions and the question of screen effectiveness on fish as small as delta smelt (DSBR, CCVFCA, DWR),

- predation by birds should be considered as a potential mortality factor (DW),

- changes in carbon-nitrogen-phosphorus ratios due to sewage treatment may affect productivity of the food chain (DW),

- water diversion is the cause of the situation and
  consideration should be given to upgrading the listing to
  Endangered (PCL, HM).

We believe that some of these concerns have merit. In some cases
they are consistent with statements in our draft text and in some
cases we have modified the present text in response. Conversely,
we also disagree with some of the comments and stand by our
original analysis. Taken individually or collectively, the
technical comments do not change conclusions about the status of
the smelt population or the factors affecting it.

The SWC, CVPWA and DWR point to apparent discrepancies between
certain conclusions reached in the report and the
recommendations. The Department believes that those apparent
discrepancies are due to the draft report's failure to explain
adequately the logical basis for recommendations and that there
is no discrepancy between conclusions about the status of the
smelt population and the recommendations.

The most essential conclusions are that the Delta smelt
population fluctuated widely in abundance from 1959 through 1982,
but has been consistently at or below previous minimum levels
since 1983; the causes for their low abundance are uncertain,
although a number of impacts and likely threats are evident; and
scientific information is insufficient to determine the minimum

viable population size. In this regard, despite their technical comments, the SWC concede that there is "ample evidence to suggest that delta smelt are at a relatively low level of abundance and therefore represent a species of concern" (p. 9 Attachment 1, July 18, 1990 letter from George Baumli to Susan Cochrane), and DWR states that "it is clear that the population has been low and relatively stable for the past several years" (July 19, 1990 memorandum from Robert G. Potter to Susan Cochrane). The central issue, therefore, is whether the delta smelt is truly likely to become an endangered species in the foreseeable future and deserving of Threatened status.

The Department disagrees with PCL and HM and agrees with the SWC, CVPWA and DWR that based on available evidence there is a measure of uncertainty regarding endangerment (page 88, this report). We believe that at least three alternative conclusions about the population's status merit careful consideration. These are:

1. Some set of circumstances has caused the recent consistent low abundance levels but not permanently reduced habitat carrying capacity, so recovery may occur spontaneously.

2. Habitat degradation has permanently reduced this population to a low but stable level.

3. Habitat degradation has caused the population to fall
    to a low, temporarily stable level, but increasing
    habitat stress is likely to cause the population to
    decrease further.

The first alternative would clearly not warrant listing the
smelt. The second would warrant listing only if the present
population level is close to the minimum viable population size.
At first glance, that seems unlikely considering the rapid
historical increases from similar levels, but subsequent habitat
degradation may have affected population viability. The third
could warrant listing as threatened, depending on the likely
consequences of a further decline.

While none of the alternatives can be ruled out, the Department
concluded that the third is sufficiently likely and warrants
listing the smelt as threatened. Specific supporting reasons
are:

1. The general degradation of phytoplankton, zooplankton and
    several species of fish including delta smelt, in the Delta
    and Suisun Bay.

2. The association of some of these changes with water
    development, with reverse flows and losses in project
    diversions causing particularly important effects.

3. Those water development effects will increase unless specific mitigative actions are taken.

4. The rapid changes associated with accidental introductions of invertebrates which probably haven't stabilized yet.

5. The vulnerability of delta smelt to extinction due to their limited distribution, and life history characteristics.

6. The uncertainty about factors controlling the abundance of smelt, which leads to an inability to conclude that smelt are unlikely to be harmed by further changes.

7. Each additional year of depressed populations makes it more difficult to rationalize the situation as reflecting temporary habitat degradation.

The SWC, CVPWA and DWR all advocate comprehensive studies as an alternative to listing. The Department recommends that such studies should be part of the recovery and management actions, rather than a substitute for listing. The Department's reasons are:

1. The status of this resource is much better defined by past programs than the SWC and CVPWA believe it is.

2. Management actions are warranted now due to risks posed by continuing environmental changes, and

3. Experience indicates that conclusive results will not be achieved quickly by proposed studies.

In addition to studies, DWR advanced two management recommendations as follows:

- The species list for the 1986 DFG-DWR agreement to offset DWR's direct Delta pumping impacts be expanded from striped bass, chinook salmon, and steelhead, to include Delta smelt. This action would result in funds being made available to develop projects to offset DWR's entrainment losses.

- The present DFG/DWR/USBR negotiations to develop an agreement to offset CVP/SWP indirect Delta impacts be expanded to include Delta smelt. (The negotiations presently focus on striped bass and chinook salmon).

The Department considers these helpful, but not specific enough. They would logically lead to consideration of the specific measures included in our recommendations. The lack of certainty as to the cause of the decline creates uncertainty as to the measures which should be undertaken to increase the population. The Department has chosen to recommend a series of habitat

improvement measures related to the life history of smelt. The
Department is confident that the recommended measures would
improve habitat quality in the Delta and Suisun Bay and have a
high probability of increasing smelt abundance.

Proposals to modify CVP/SWP pumping strategies to reduce
entrainment losses, and to augment Delta outflow, have drawn
specific criticism, considering the lack of strong relationships
between entrainment losses, outflow and smelt abundance found
during the analysis. While strong, long-term relationships do
not exist, the Department considers the drain of present water
diversions on the delta smelt population to be a significant
factor inhibiting their recovery and flow augmentation is worth
considering, at least as a vehicle to reduce such losses.
Greater flows would reduce these losses by transporting the smelt
population downstream away from the diversions.

In response to concerns about screening delta agricultural
diversions we have modified our draft recommendation to include
an initial evaluation phase.

Appendix C.   Delta smelt abundance indices for the townet
survey for the years 1959-1965 and 1969-1989

Year	Survey 1	Survey 2	Mean
1959	0.1	22.2	11.1
1960	21.6	26.0	23.8
1961	18.9	17.0	18.0
1962	20.3	26.5	23.5
1963	1.3	2.1	1.7
1964	11.4	36.4	23.9
1965	6.4	5.3	5.9
1969	3.7	1.2	2.7
1970	20.3	43.4	31.9
1971	8.9	15.8	12.4
1972	9.2	12.8	11.0
1973	21.5	21.0	21.2
1974	12.0	13.8	13.0
1975	7.0	16.7	11.9
1976	63.0	38.2	50.6
1977	12.5	37.1	24.8
1978	23.0	102.0	62.5
1979	6.4	19.9	13.2
1980	14.7	16.9	15.8
1981	19.1	20.5	19.9
1982	7.0	14.3	10.6
1983	3.3	2.5	2.9
1984	1.3	1.2	1.3
1985	0.8	0.9	0.9
1986	7.4	8.3	7.8
1987	0.4	2.4	1.4
1988	0.5	1.8	1.2
1989	3.6	0.8	2.2

1990

Appendix D. Weight Factors used for Midwater Trawl Survey Data.

Area	Midwater Trawl Stations	Acre ft.
1	336-339	81,000
2	320	28,000
3	321-326	113,000
4	327-329	65,000
5	330-335	122,000
6	317-319	59,000
7	312-316	102,000
8	303-311	185,000
9	301-302	30,000
10	340	48,000
11	401-402,404-408	160,000
12	409-419	140,000
13	501-520	180,000
14	601-606,608	50,000
15	702-711	120,000
16	801-815	140,000
17	901-915,918,919	200,000

Appendix E. Regression search of potential effects of March to June environmental variables on the summer townet survey abundance index for delta smelt. See appendix H for Key to variable names.

N=16   REGRESSION MODELS FOR DEPENDENT VARIABLE: TNS_IND   MODEL: MODEL1

NUMBER IN MODEL	R-SQUARE	ADJUSTED R-SQUARE	SSE	C(P)	VARIABLES IN MODEL
1	0.00245546	-.06879772	4445.9463	0.126004	MR_J_PT
1	0.00918957	-.06158261	4415.9331	0.0441457	DAY_REVS
1	0.01253711	-.05799595	4401.0135	0.00345339	LMJM_OT2
1	0.01280421	-.05770977	4399.8230	.000206564	LMJM_OUT
1	0.07543021	0.00938952	4120.7058	-0.761066	MJM_EXP
1	0.07861687	0.01280379	4106.5033	-0.799802	MJM_COP
1	0.18925268	0.13134216	3613.4216	-2.1447	MJM_WT
2	0.00918957	-.14324280	4415.9331	2.044146	MR_J_PT DAY_REVS
2	0.01286260	-.13900470	4399.5628	1.999497	LMJM_OT2 DAY_REVS
2	0.01312179	-.13870563	4398.4076	1.996346	LMJM_OUT DAY_REVS
2	0.01320068	-.13861460	4398.0560	1.995387	LMJM_OUT LMJM_OT2
2	0.01612688	-.13523821	4385.0143	1.959817	LMJM_OT2 MR_J_PT
2	0.01624085	-.13510671	4384.5063	1.958431	LMJM_OUT MR_J_PT
2	0.07582923	-.06635089	4118.9275	1.234084	MR_J_PT MJM_EXP
2	0.07861957	-.06313127	4106.4912	1.200165	MR_J_PT MJM_COP
2	0.08363359	-.05734586	4084.1443	1.139215	LMJM_OUT MJM_EXP
2	0.08412034	-.05678422	4081.9749	1.133298	LMJM_OUT MJM_COP
2	0.08465013	-.05617293	4079.6137	1.126858	LMJM_OT2 MJM_EXP
2	0.08472391	-.05608780	4079.2849	1.125961	LMJM_OT2 MJM_COP
2	0.09867377	-.03999180	4017.1118	0.956389	MJM_COP MJM_EXP
2	0.10366083	-.03423751	3994.8851	0.895767	MJM_COP DAY_REVS
2	0.11678410	-.01909527	3936.3961	0.736242	MJM_EXP DAY_REVS
2	0.19818343	0.07482704	3573.6082	-0.253236	MJM_COP MJM_WT
2	0.23032862	0.11191764	3430.3407	-0.643988	MJM_WT MJM_EXP
2	0.24841852	0.13279060	3349.7160	-0.863886	MJM_WT DAY_REVS
2	0.26355320	0.15025369	3282.2624	-1.0479	MR_J_PT MJM_WT
2	0.27339677	0.16161165	3238.3907	-1.1675	LMJM_OT2 MJM_WT
2	0.27615854	0.16479831	3226.0818	-1.2011	LMJM_OUT MJM_WT
3	0.01376476	-.23279405	4395.5420	3.988530	LMJM_OUT LMJM_OT2 DAY_REVS
3	0.01620227	-.22974717	4384.6783	3.958900	LMJM_OT2 MR_J_PT DAY_REVS
3	0.01624333	-.22969583	4384.4953	3.958401	LMJM_OUT LMJM_OT2 MR_J_PT
3	0.01635587	-.22955517	4383.9937	3.957033	LMJM_OUT MR_J_PT DAY_REVS
3	0.09103191	-.13621011	4051.1708	3.049282	LMJM_OUT LMJM_OT2 MJM_COP
3	0.09227006	-.13466242	4045.6525	3.034231	LMJM_OUT MR_J_PT MJM_COP
3	0.09440191	-.13199761	4036.1511	3.008317	LMJM_OT2 MR_J_PT MJM_COP
3	0.09830425	-.12711969	4018.7588	2.960881	LMJM_OUT LMJM_OT2 MJM_EXP
3	0.09945417	-.12568229	4013.6337	2.946902	MR_J_PT MJM_COP MJM_EXP
3	0.10405786	-.11992768	3993.1156	2.890941	LMJM_OUT MR_J_PT MJM_EXP
3	0.10407978	-.11990027	3993.0179	2.890674	LMJM_OUT MJM_COP MJM_EXP
3	0.10506134	-.11867333	3988.6432	2.878743	LMJM_OT2 MJM_COP MJM_EXP
3	0.10912856	-.11358930	3970.5160	2.829302	LMJM_OT2 MR_J_PT MJM_EXP
3	0.11010825	-.11236468	3966.1496	2.817393	LMJM_OT2 MJM_COP DAY_REVS
3	0.11104587	-.11119266	3961.9708	2.805995	LMJM_OUT MJM_COP DAY_REVS
3	0.11671103	-.10411121	3936.7218	2.737131	MR_J_PT MJM_COP DAY_REVS
3	0.13234922	-.08456348	3867.0241	2.547035	LMJM_OT2 MJM_EXP DAY_REVS
3	0.13521623	-.08097971	3854.2461	2.512184	LMJM_OUT MJM_EXP DAY_REVS
3	0.14131462	-.07335673	3827.0663	2.438053	MJM_COP MJM_EXP DAY_REVS
3	0.16007633	-.04990458	3743.4474	2.209988	MR_J_PT MJM_EXP DAY_REVS
3	0.23074451	0.03843063	3428.4871	1.350956	MJM_COP MJM_WT MJM_EXP
3	0.26162025	0.07702532	3290.8773	0.975635	MJM_COP MJM_WT DAY_REVS
3	0.26528200	0.08160251	3274.5573	0.931124	MR_J_PT MJM_COP MJM_WT
3	0.27343085	0.09178857	3238.2388	0.832068	LMJM_OT2 MJM_COP MJM_WT
3	0.27545584	0.09431980	3229.2136	0.807452	MR_J_PT MJM_WT MJM_EXP
3	0.27589325	0.09486656	3227.2641	0.802135	LMJM_OT2 MJM_WT DAY_REVS
3	0.27642018	0.09552522	3224.9157	0.795730	LMJM_OUT MJM_COP MJM_WT
3	0.27849796	0.09812244	3215.6552	0.770473	LMJM_OUT MJM_WT DAY_REVS
3	0.28085861	0.10107326	3205.1341	0.741777	LMJM_OT2 MR_J_PT MJM_WT
3	0.28206293	0.10257866	3199.7666	0.727137	MR_J_PT MJM_WT DAY_REVS
3	0.28209759	0.10262199	3199.6121	0.726716	LMJM_OUT LMJM_OT2 MJM_WT
3	0.28338380	0.10422975	3193.8796	0.711081	LMJM_OUT MR_J_PT MJM_WT
3	0.30087076	0.12608844	3115.9421	0.498512	LMJM_OT2 MJM_WT MJM_EXP
3	0.30091448	0.12614311	3115.7472	0.497981	LMJM_OUT MJM_WT MJM_EXP
3	0.33438849	0.16798562	2966.5573	0.0910754	MJM_WT MJM_EXP DAY_REVS

Appendix F. Regression search of potential effects of March to June
environmental variables on the fall midwater trawl
abundance index for delta smelt. See appendix H for Key
to variable names.

N=14   REGRESSION MODELS FOR DEPENDENT VARIABLE: MWT_IND   MODEL: MODEL1

NUMBER IN MODEL	R-SQUARE	ADJUSTED R-SQUARE	SSE	C(P)	VARIABLES IN MODEL
1	0.00014336	-.08317803	2920645.8	25.430383	LMJB_OT2
1	0.00085631	-.08240566	2918562.5	25.405119	LMJB_OUT
1	0.00249623	-.08062909	2913772.2	25.347008	DAY_REVS
1	0.00398817	-.07901282	2909414.1	25.294140	MJB_EXP
1	0.01024312	-.07223662	2891143.0	25.072493	MR_J_PT
1	0.15752201	0.08731551	2460932.0	19.853598	MJB_COP
1	0.30782448	0.25014319	2021888.9	14.527560	MJB_WT
2	0.00261506	-.17872766	2913425.1	27.342797	LMJB_OUT DAY_REVS
2	0.00388605	-.17722558	2909712.4	27.297759	LMJB_OT2 DAY_REVS
2	0.00414336	-.17692148	2908960.8	27.288641	LMJB_OT2 MJB_EXP
2	0.00471141	-.17625015	2907301.5	27.268512	MJB_EXP DAY_REVS
2	0.00497157	-.17594269	2906541.5	27.259293	LMJB_OUT MJB_EXP
2	0.01024325	-.16971253	2891142.6	27.072489	MR_J_PT DAY_REVS
2	0.01533291	-.16369747	2876275.4	26.892134	LMJB_OUT MR_J_PT
2	0.01740101	-.16125335	2870234.3	26.818850	MR_J_PT MJB_EXP
2	0.02046772	-.15762906	2861276.3	26.710180	LMJB_OT2 MR_J_PT
2	0.11181617	-.04967180	2594441.6	23.473205	LMJB_OUT LMJB_OT2
2	0.15782147	0.00469810	2460057.2	21.842986	MJB_COP DAY_REVS
2	0.16523995	0.01346540	2438387.4	21.580109	LMJB_OT2 MJB_COP
2	0.17041767	0.01958451	2423262.9	21.396634	LMJB_OUT MJB_COP
2	0.20420359	0.05951333	2324572.1	20.199414	MR_J_PT MJB_COP
2	0.21899222	0.07699080	2281373.6	19.675372	MJB_COP MJB_EXP
2	0.31695692	0.19276727	1995212.4	16.203948	MJB_WT MJB_EXP
2	0.32616822	0.20365336	1968305.6	15.877541	MJB_WT DAY_REVS
2	0.32638517	0.20390974	1967671.9	15.869853	MR_J_PT MJB_WT
2	0.33487614	0.21394453	1942869.2	15.568972	MJB_COP MJB_WT
2	0.33694797	0.21639306	1936817.3	15.495555	LMJB_OUT MJB_WT
2	0.34287576	0.22339862	1919501.8	15.285502	LMJB_OT2 MJB_WT
3	0.00496994	-.29353907	2906546.3	29.259351	LMJB_OT2 MJB_EXP DAY_REVS
3	0.00497666	-.29353034	2906526.7	29.259151	LMJB_OUT MJB_EXP DAY_REVS
3	0.01863274	-.27577743	2866636.4	28.775203	LMJB_OUT MR_J_PT DAY_REVS
3	0.02118697	-.27245694	2859175.3	28.684693	MR_J_PT MJB_EXP DAY_REVS
3	0.02510041	-.26736946	2847743.9	28.546018	LMJB_OUT MR_J_PT MJB_EXP
3	0.02767892	-.26401740	2840211.9	28.454648	LMJB_OT2 MR_J_PT DAY_REVS
3	0.03257719	-.25764965	2825903.8	28.281075	LMJB_OT2 MR_J_PT MJB_EXP
3	0.12622952	-.13590162	2552339.3	24.962461	LMJB_OUT LMJB_OT2 DAY_REVS
3	0.17316716	-.07488269	2415231.5	23.299204	LMJB_OUT LMJB_OT2 MR_J_PT
3	0.17906853	-.06721092	2397993.2	23.090087	LMJB_OUT LMJB_OT2 MJB_EXP
3	0.18625393	-.05786989	2377004.2	22.835469	LMJB_OT2 MJB_COP DAY_REVS
3	0.20229296	-.03701916	2330153.2	22.267118	LMJB_OUT MJB_COP DAY_REVS
3	0.20895398	-.02835982	2310695.9	22.031082	LMJB_OUT MR_J_PT MJB_COP
3	0.21723206	-.01759832	2286515.1	21.737744	LMJB_OT2 MR_J_PT MJB_COP
3	0.22625222	-.00587211	2260166.6	21.418111	MJB_COP MJB_EXP DAY_REVS
3	0.23358763	0.00366392	2238739.4	21.158177	MR_J_PT MJB_COP DAY_REVS
3	0.23487803	0.00534144	2234978.1	21.112451	LMJB_OT2 MJB_COP MJB_EXP
3	0.24073285	0.01295271	2217867.8	20.904983	LMJB_OUT MJB_COP MJB_EXP
3	0.26236440	0.04107372	2154680.7	20.138459	MR_J_PT MJB_COP MJB_EXP
3	0.32890932	0.12758212	1960298.7	17.780409	MJB_WT MJB_EXP DAY_REVS
3	0.33375731	0.13388450	1946137.4	17.608618	MR_J_PT MJB_WT DAY_REVS
3	0.33736038	0.13856849	1935612.6	17.480942	LMJB_OUT MR_J_PT MJB_WT
3	0.33743693	0.13866801	1935389.8	17.478229	LMJB_OUT MJB_WT DAY_REVS
3	0.33779659	0.13913557	1934338.4	17.465404	MR_J_PT MJB_COP MJB_WT
3	0.34287576	0.14573849	1919501.8	17.285502	LMJB_OT2 MR_J_PT MJB_WT
3	0.34288982	0.14575676	1919466.8	17.285004	LMJB_OT2 MJB_WT DAY_REVS
3	0.34714188	0.15128444	1907040.2	17.134330	LMJB_OUT MJB_COP MJB_WT
3	0.34993780	0.15491913	1898873.2	17.035255	MR_J_PT MJB_WT MJB_EXP
3	0.35160616	0.15708801	1893999.8	16.976136	LMJB_OUT MJB_WT MJB_EXP
3	0.35227786	0.15796122	1892037.7	16.952334	LMJB_OT2 MJB_COP MJB_WT
3	0.35452653	0.16088488	1885469.2	16.872651	MJB_COP MJB_WT DAY_REVS
3	0.35668059	0.16369517	1879153.7	16.796037	LMJB_OT2 MJB_WT MJB_EXP
3	0.39365370	0.21174981	1771176.2	15.486162	MJB_COP MJB_WT MJB_EXP
3	0.43054898	0.25971367	1663402.8	14.178768	LMJB_OUT LMJB_OT2 MJB_WT
3	0.44276665	0.27559664	1627714.2	13.745022	LMJB_OUT LMJB_OT2 MJB_COP

Appendix G. Regression search of potential effects of July to October environmental variables on the fall midwater trawl abundance index for delta smelt. See appendix H for Key to variable names.

N=14   REGRESSION MODELS FOR DEPENDENT VARIABLE: MWT_IND   MODEL: MODEL1

NUMBER IN MODEL	R-SQUARE	ADJUSTED R-SQUARE	SSE	C(P)	VARIABLES IN MODEL
1	0.00130751	-.08191686	2917244.5	28.059097	LJ_O_OT2
1	0.00303352	-.08004702	2912202.7	27.993321	J_O_EXP
1	0.00353265	-.07950629	2910744.7	27.974300	LJ_O_OUT
1	0.00571686	-.07714007	2904364.5	27.891062	JL_OPT
1	0.03338527	-.04716596	2823543.3	26.836649	DAY_REVF
1	0.25866386	0.19688585	2165490.2	18.251524	JL_O_COP
1	0.36666982	0.31389231	1849997.9	14.135532	JO_WT
2	0.00416421	-.17689684	2908899.9	29.950232	LJ_O_OT2 J_O_EXP
2	0.00612686	-.17457734	2903166.8	29.875437	J_O_EXP JL_OPT
2	0.00641868	-.17423247	2902314.4	29.864316	LJ_O_OUT J_O_EXP
2	0.01694467	-.16179267	2871567.4	29.463182	LJ_O_OT2 JL_OPT
2	0.02384620	-.15363630	2851407.5	29.200172	LJ_O_OUT JL_OPT
2	0.03911606	-.13559011	2806803.3	28.618254	J_O_EXP DAY_REVF
2	0.04152319	-.13274532	2799771.9	28.526521	LJ_O_OUT DAY_REVF
2	0.04255564	-.13152516	2796756.1	28.487176	JL_OPT DAY_REVF
2	0.04948508	-.12333582	2776514.7	28.223102	LJ_O_OT2 DAY_REVF
2	0.26318064	0.12921348	2152296.4	20.079394	JL_O_COP JL_OPT
2	0.26445781	0.13072287	2148565.7	20.030722	JL_O_COP J_O_EXP
2	0.26531810	0.13173957	2146052.7	19.997938	LJ_O_OT2 JL_O_COP
2	0.26691795	0.13363030	2141379.4	19.936969	LJ_O_OUT LJ_O_OT2
2	0.26859214	0.13560889	2136489.0	19.873167	LJ_O_OUT JL_O_COP
2	0.31324298	0.18837807	2006061.1	18.171572	JL_O_COP DAY_REVF
2	0.36701013	0.25192106	1849003.8	16.122564	JO_WT DAY_REVF
2	0.36713721	0.25207125	1848632.6	16.117721	JO_WT J_O_EXP
2	0.37098812	0.25662232	1837383.8	15.970967	LJ_O_OUT JO_WT
2	0.37199556	0.25781294	1834441.0	15.932574	LJ_O_OT2 JO_WT
2	0.37826357	0.26522058	1816131.8	15.693707	JO_WT JL_OPT
2	0.69578315	0.64047099	888636.8	3.593377	JL_O_COP JO_WT
3	0.01861599	-.27579921	2866685.3	31.399490	LJ_O_OT2 J_O_EXP JL_OPT
3	0.02641678	-.26565819	2843898.7	31.102210	LJ_O_OUT J_O_EXP JL_OPT
3	0.04333182	-.24366863	2794488.8	30.457596	LJ_O_OUT JL_OPT DAY_REVF
3	0.04948922	-.23566401	2776502.6	30.222944	LJ_O_OT2 JL_OPT DAY_REVF
3	0.08124338	-.19438361	2683746.7	29.012827	LJ_O_OUT J_O_EXP DAY_REVF
3	0.08699869	-.18690170	2666935.1	28.793499	J_O_EXP JL_OPT DAY_REVF
3	0.10105707	-.16862581	2625669.7	28.257749	LJ_O_OT2 J_O_EXP DAY_REVF
3	0.26560361	0.04528469	2145218.7	21.987057	JL_O_COP J_O_EXP JL_OPT
3	0.27059762	0.05177691	2130630.9	21.796741	LJ_O_OT2 JL_O_COP J_O_EXP
3	0.27207674	0.05369976	2126310.3	21.740373	LJ_O_OUT LJ_O_OT2 JL_OPT
3	0.27409046	0.05631760	2120428.1	21.663632	LJ_O_OUT JL_O_COP J_O_EXP
3	0.28798367	0.07437877	2079845.1	21.134177	LJ_O_OT2 JL_O_COP JL_OPT
3	0.29533035	0.08392946	2058385.0	20.854203	LJ_O_OUT JL_O_COP JL_OPT
3	0.31995144	0.11593687	1986465.2	19.915920	LJ_O_OUT JL_O_COP DAY_REVF
3	0.32121710	0.11758223	1982768.2	19.867687	JL_O_COP J_O_EXP DAY_REVF
3	0.32180560	0.11834728	1981049.1	19.845260	JL_O_COP JL_OPT DAY_REVF
3	0.32573019	0.12344924	1969585.1	19.695698	LJ_O_OT2 JL_O_COP DAY_REVF
3	0.36717777	0.17733109	1848514.1	18.116175	JO_WT J_O_EXP DAY_REVF
3	0.37146369	0.18290279	1835994.7	17.952843	LJ_O_OUT JO_WT J_O_EXP
3	0.37216045	0.18380859	1833959.4	17.926290	LJ_O_OUT JO_WT DAY_REVF
3	0.37238843	0.18410495	1833293.5	17.917603	LJ_O_OT2 JO_WT J_O_EXP
3	0.37388822	0.18605468	1828912.5	17.860447	LJ_O_OT2 JO_WT DAY_REVF
3	0.37947638	0.19331930	1812589.1	17.647488	JO_WT J_O_EXP JL_OPT
3	0.38020262	0.19426341	1810467.7	17.619812	JO_WT JL_OPT DAY_REVF
3	0.40937631	0.23218921	1725249.5	16.508034	LJ_O_OUT LJ_O_OT2 JO_WT
3	0.40963462	0.23252501	1724494.9	16.498190	LJ_O_OUT LJ_O_OT2 J_O_EXP
3	0.42150144	0.24795187	1689831.2	16.045959	LJ_O_OUT JO_WT JL_OPT
3	0.42446933	0.25181013	1681161.8	15.932855	LJ_O_OT2 JO_WT JL_OPT
3	0.43376093	0.26388922	1654020.4	15.578762	LJ_O_OUT LJ_O_OT2 JL_O_COP
3	0.43547960	0.26612348	1649000.1	15.513266	LJ_O_OUT LJ_O_OT2 DAY_REVF
3	0.69580992	0.60455290	888558.6	5.592357	JL_O_COP JO_WT J_O_EXP
3	0.69621217	0.60507582	887383.6	5.577028	JL_O_COP JO_WT DAY_REVF
3	0.69679479	0.60583323	885681.8	5.554825	LJ_O_OT2 JL_O_COP JO_WT
3	0.69680044	0.60584057	885665.3	5.554609	LJ_O_OUT JL_O_COP JO_WT
3	0.71429518	0.62858374	834562.0	4.887903	JL_O_COP JO_WT JL_OPT

Appendix H. Key to the variables used in regression search of environmental variables affecting delta smelt abundance.

March-June Variables

LMJN_OUT= Log_{10} Mean March-June Delta outflow.

LMJN_OT2= Log_{10} Mean March-June Delta outflow squared.

DAY_REVS=   Number of March-June days of reverse flow.

MJN_EXP=   Mean March-June water project exports.

MR_J_FT=   Mean Maximum March-June Sacramento River Temperature at Freeport.

MJN_COP=   Mean March-June copepod density/m^3 exclusive of Sinocalanus and nauplii.

MJN_WT=   Mean March-June water transparency (secchi).

July-October Variables

LJ_O_OUT= Log_{10} mean July-October Delta outflow.

LJ_O_OT2= Log_{10} mean July-October Delta outflow squared.

DAY_REVF=   Number of July-October days of reverse flows.

J_O_EXP=   Mean July-October water project exports.

J_OFT=   Mean July-October maximum Sacramento River temperature at Freeport.

JL_O_COP=   Mean July-October copepod density/m^3 exclusive ofSinocalnus and nauplii.

JO_WT=   Mean July-October water transparency (secchi).